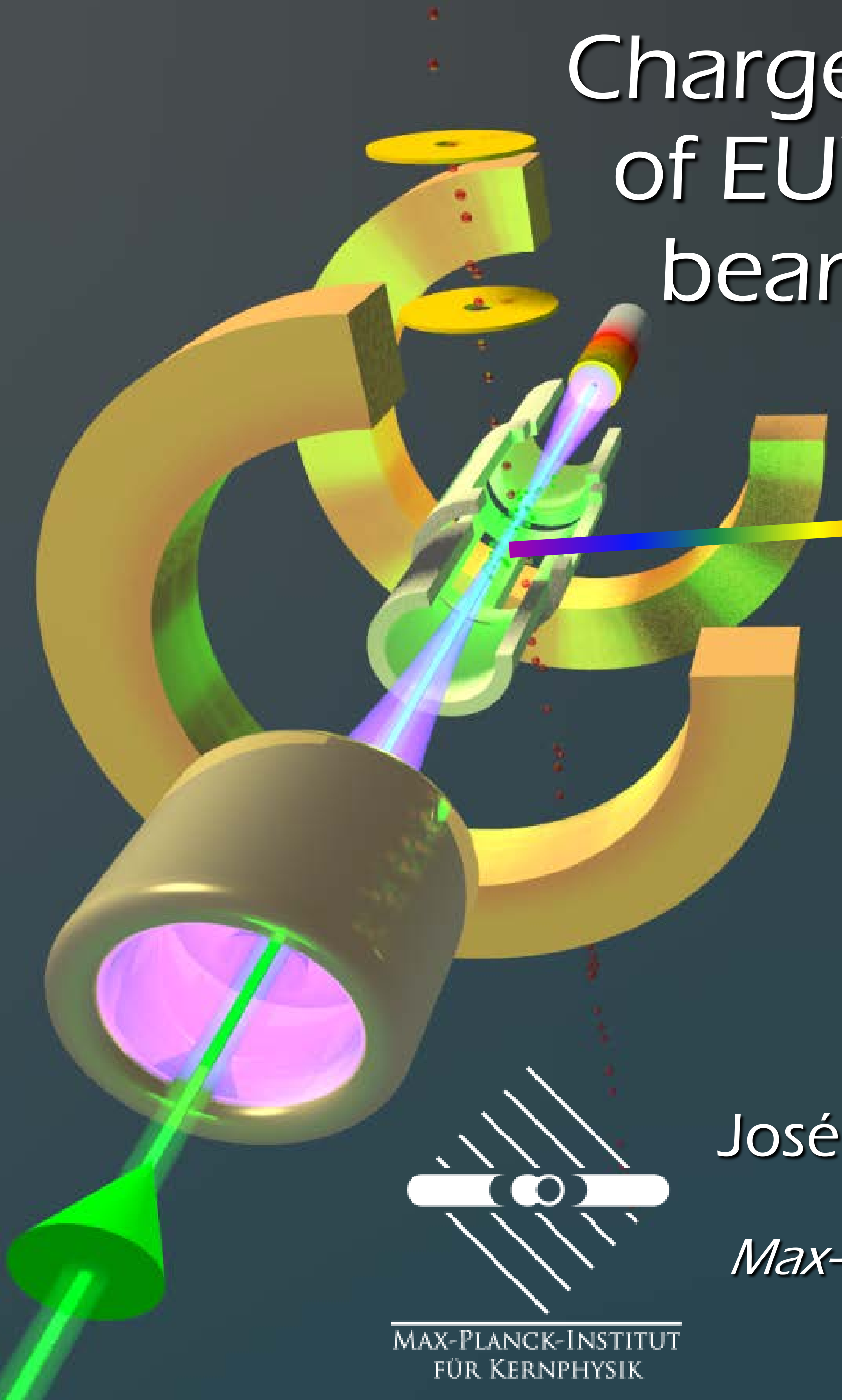
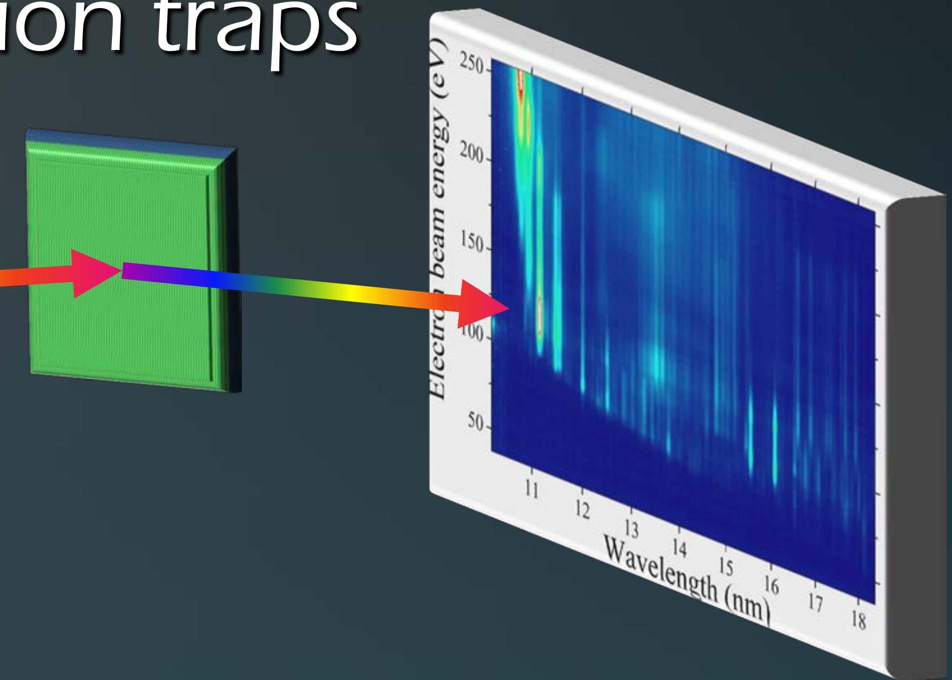
Charge-state resolving analysis of EUV spectra with electron beam ion traps





José R. Crespo López-Urrutia

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Heidelberg

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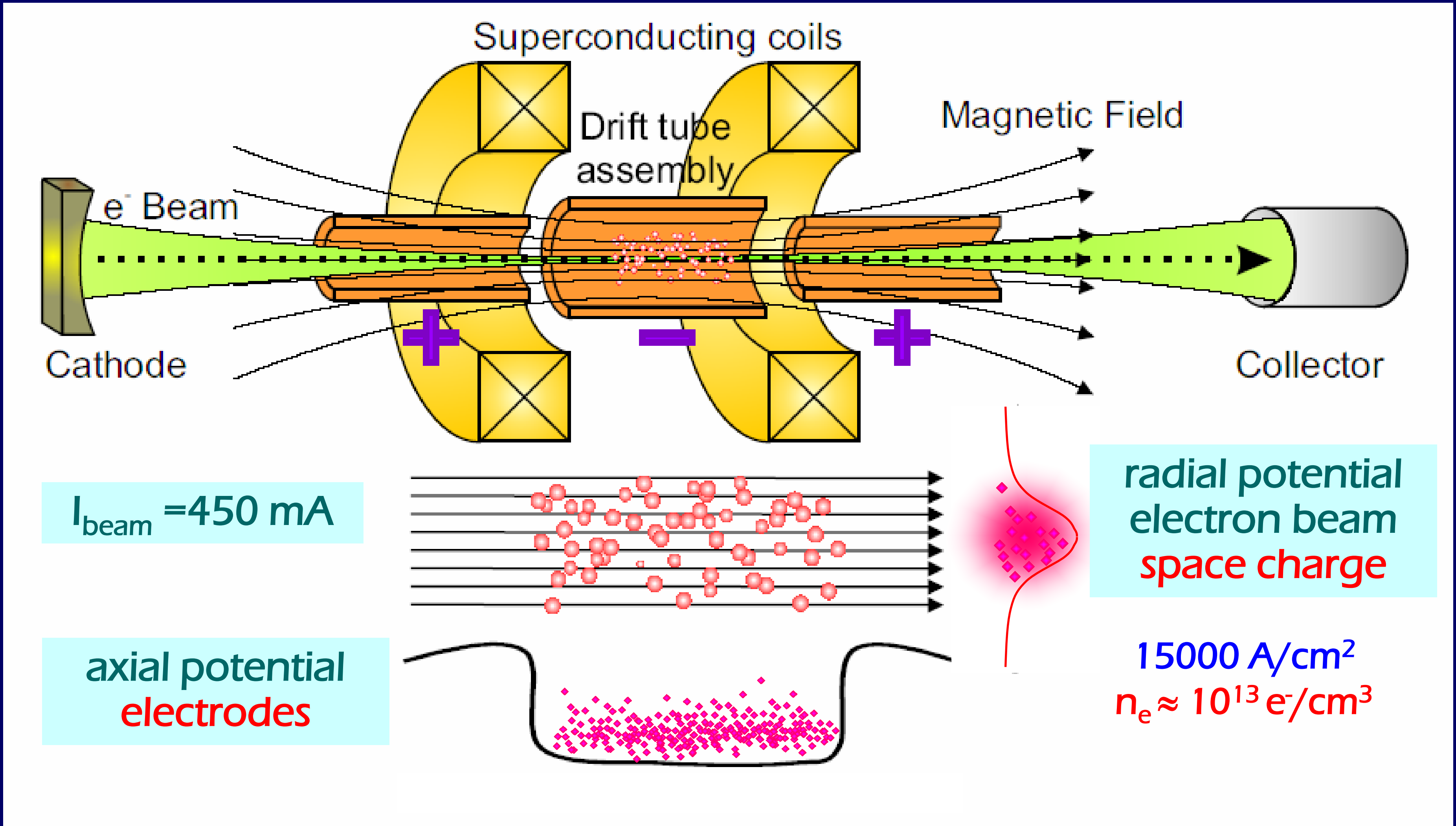
Overview

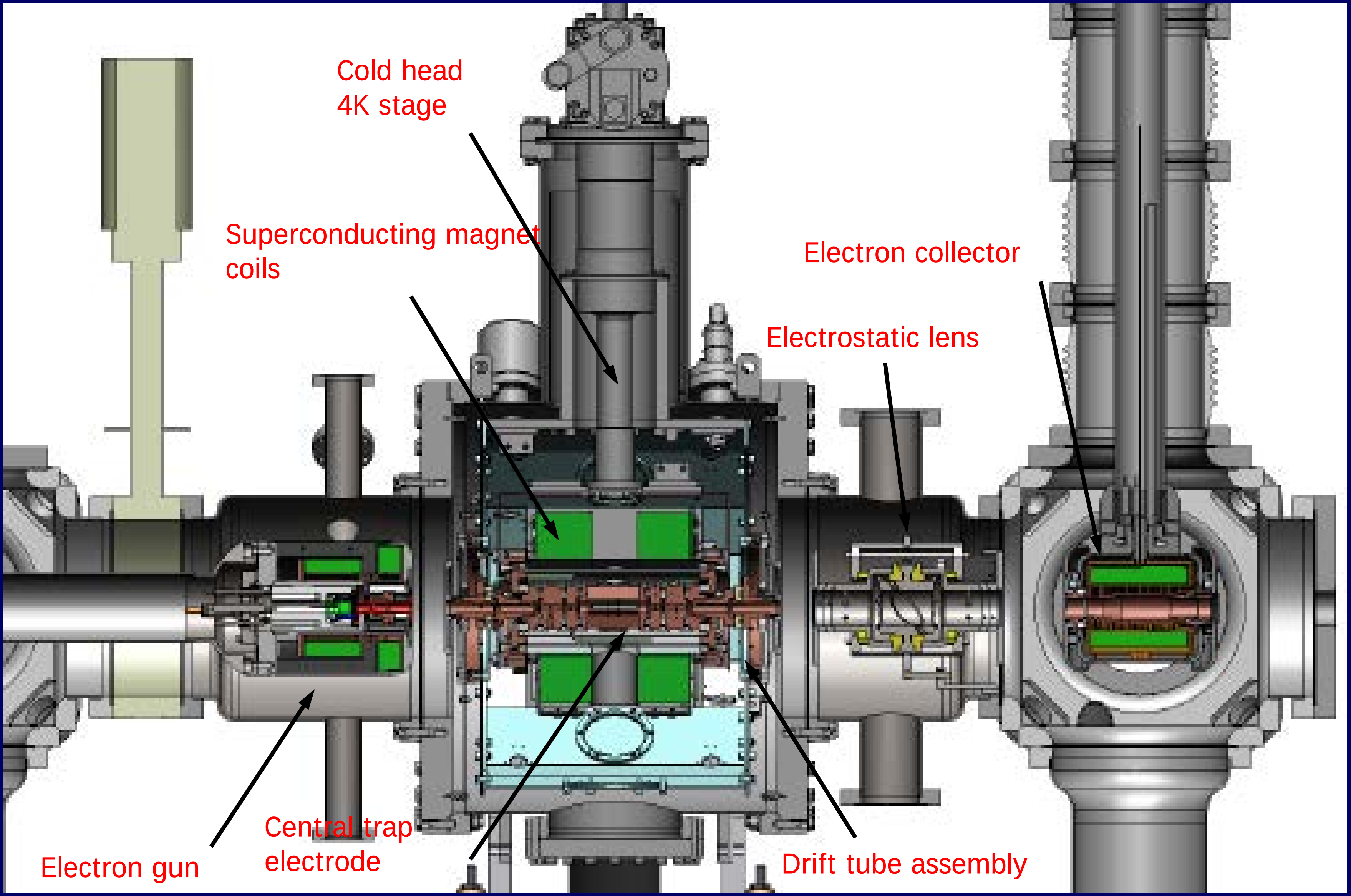
- Electron beam ion traps
- Photon excitation studies
- Electron excitation studies
- Optical and EUV spectroscopy of Sn
- Conclusions

HCI production with electron beam ion trap

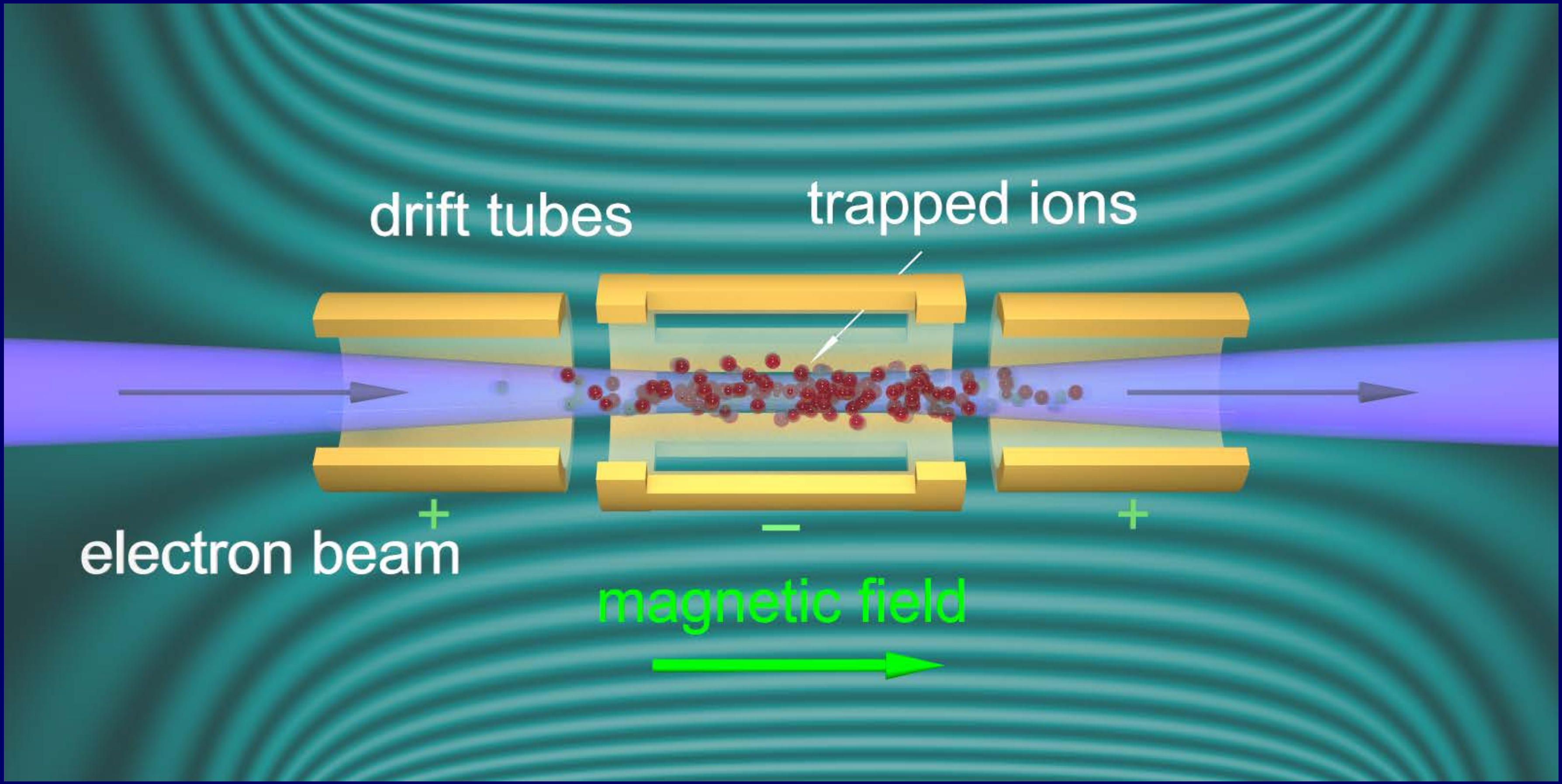


Electron beam drives ionization, excites and traps the ions inside a cylindrical volume

EBIT design MPIK Heidelberg

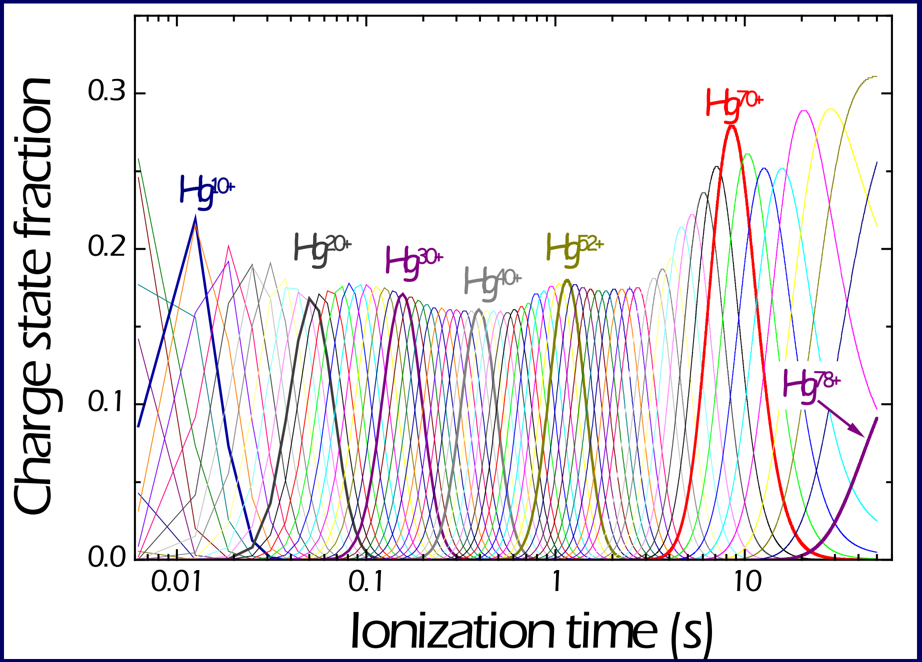


HCI production with electron beam ion trap



Electron beam drives ionization, excites and traps the ions inside a cylindrical volume

Time evolution of the charge state

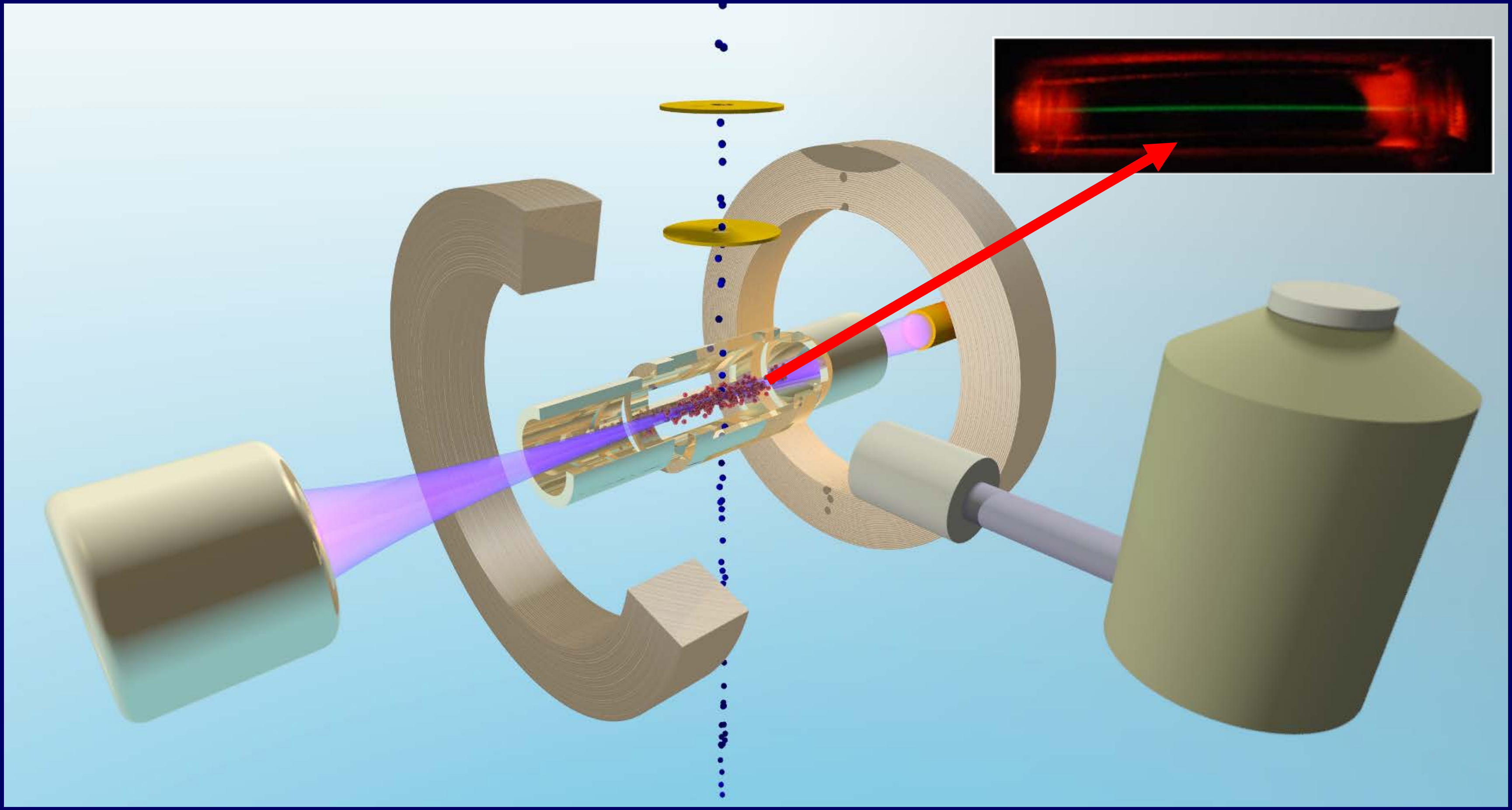


- Time evolution of mean charge state governed by electron beam energy (microsecond to second scale)
- Unscrambling atomic physics processes possible due to monoenergetic electron beam ($E/\Delta E \approx 1000$)

$$\frac{dn_0}{dt} = -n_0 \sigma_{0,1} j_e$$

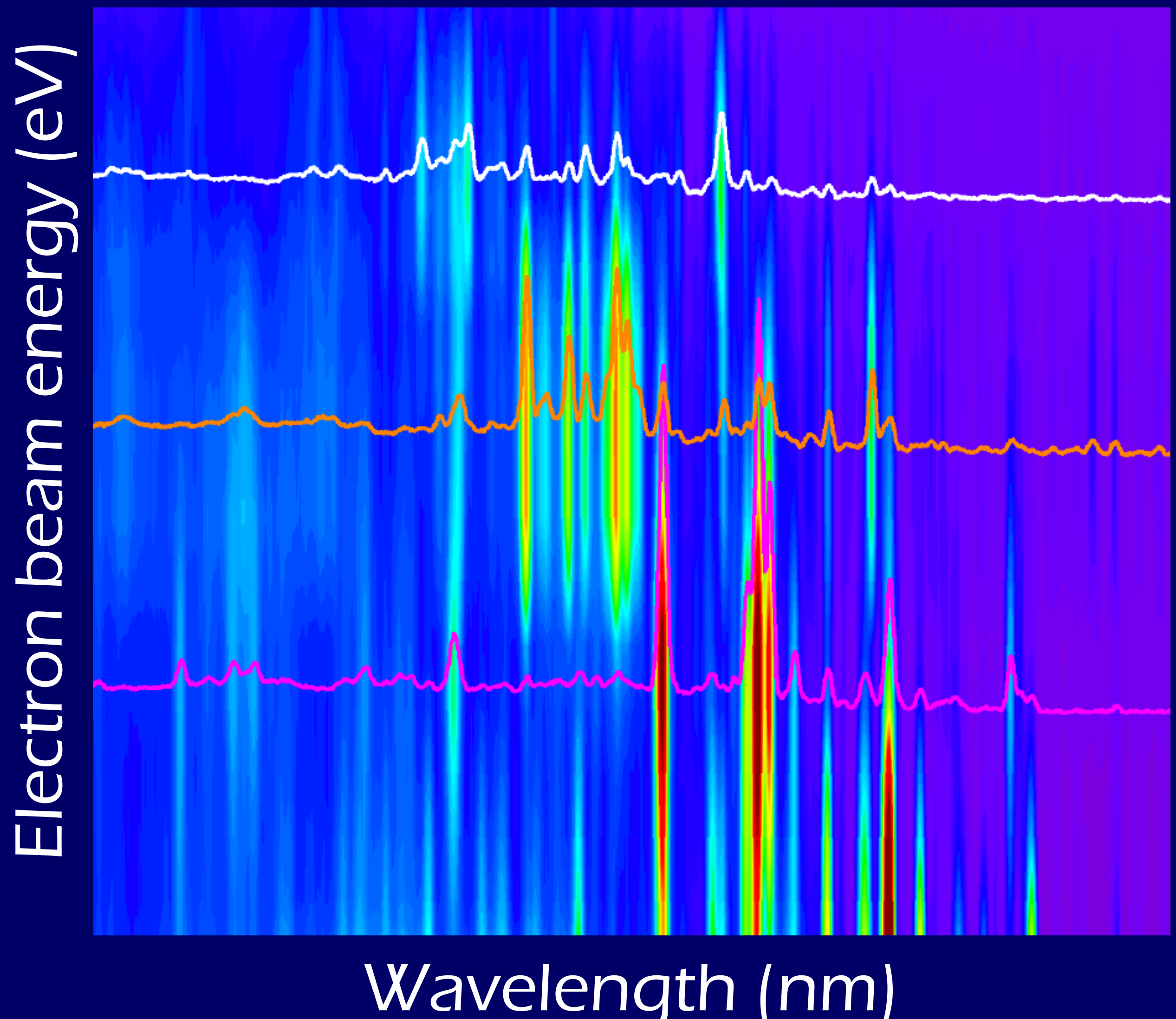
$$\frac{dn_Z}{dt} = n_{Z-1}\sigma_{Z-1,Z} j_e - n_Z \sigma_{Z,Z+1} j_e - \frac{n_Z}{\tau_{rec}(q)}$$

Strong excitation by electron impact and resonant photorecombination



Ge, Si detectors, crystal and grating spectrometers, microcalorimeters, etc., for X-ray diagnostics

Choice of charge state by dialing electron beam energy

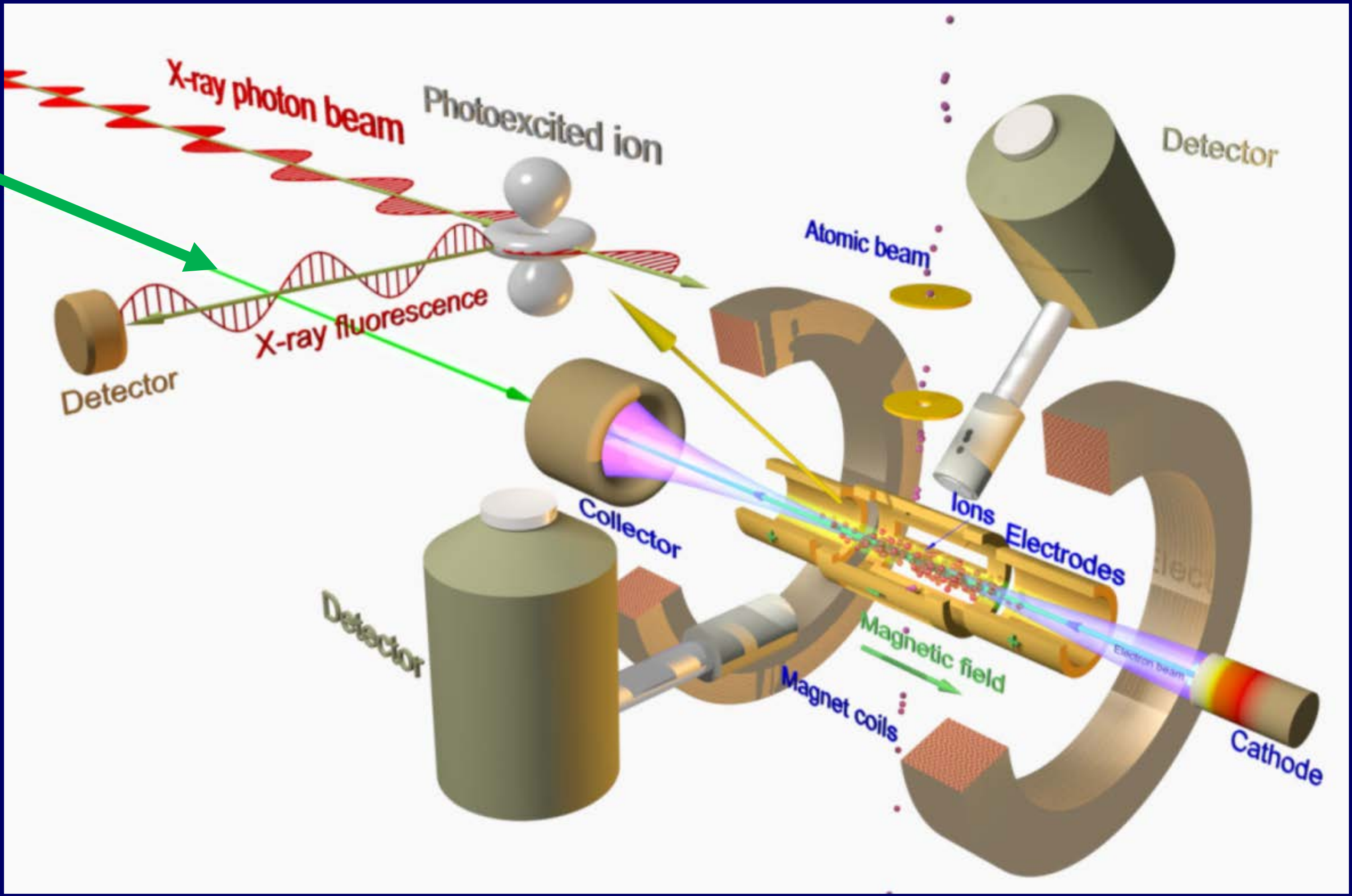


What we do with EBITs

- Photorecombination processes: radiative + dielectronic, trielectronic and quadruelectronic recombination,
- Photoionization of HCI with synchrotron radiation, from N^{3+} (from 60 eV) to Kr^{33+} (at 14 keV)
- High-resolution spectroscopy from optical to X-rays
- Free-electron laser soft x-ray spectroscopy (<800 eV)
- High-resolution x-ray metrology with synchrotron radiation (<14.4 keV)
- Laser spectroscopy of forbidden optical lines in HCI
- Sympathetic cooling of HCI for frequency metrology
- Charge-exchange studies

Free-electron laser and synchrotron-radiation excitation and photoionization of highly charged ions

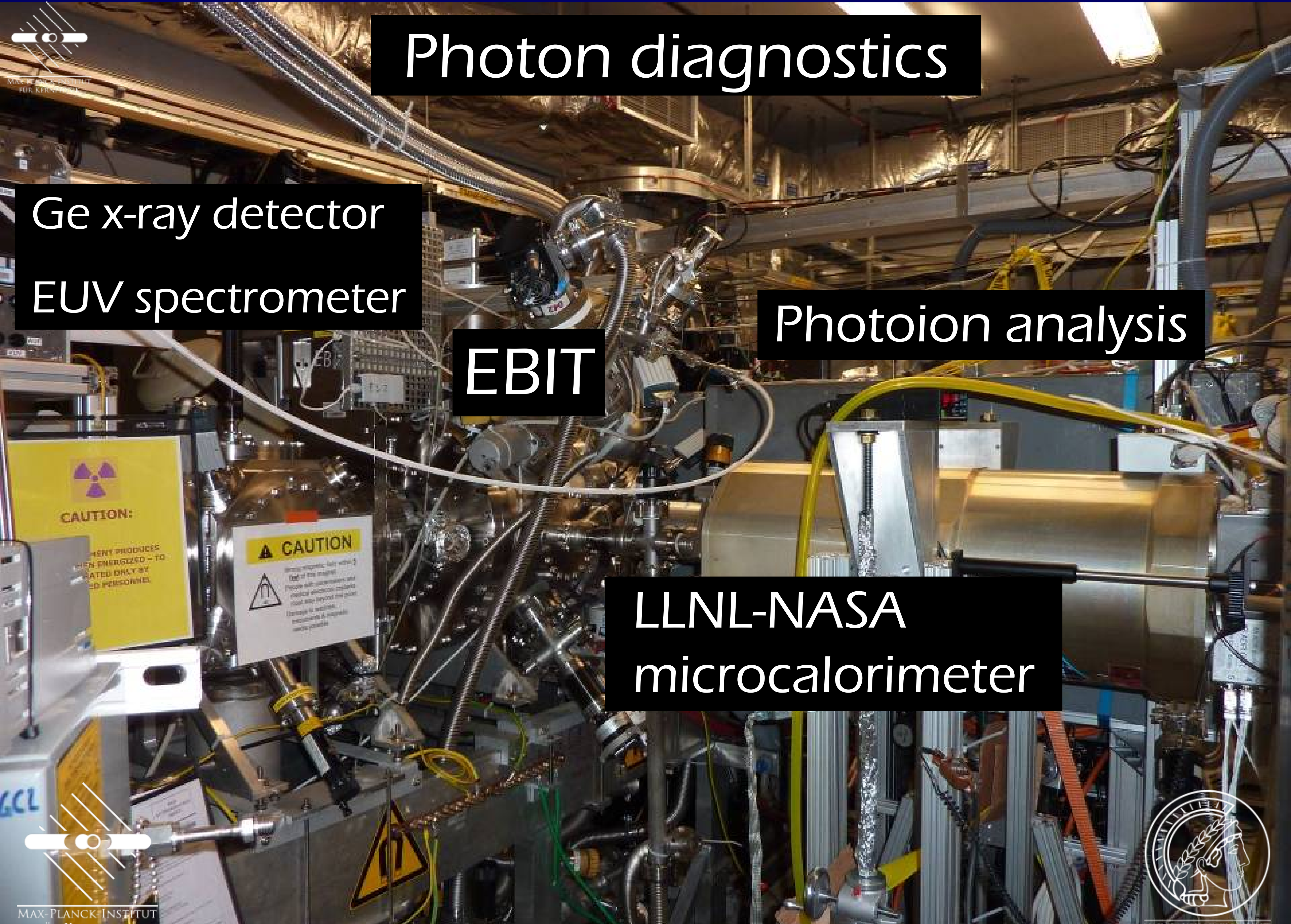
Resonant photon excitation in EBIT



- Synchrotron radiation (PETRAIII),
- Free-electron lasers (LCLS) ,

provide X-rays with high power and energy resolution

Photon diagnostics



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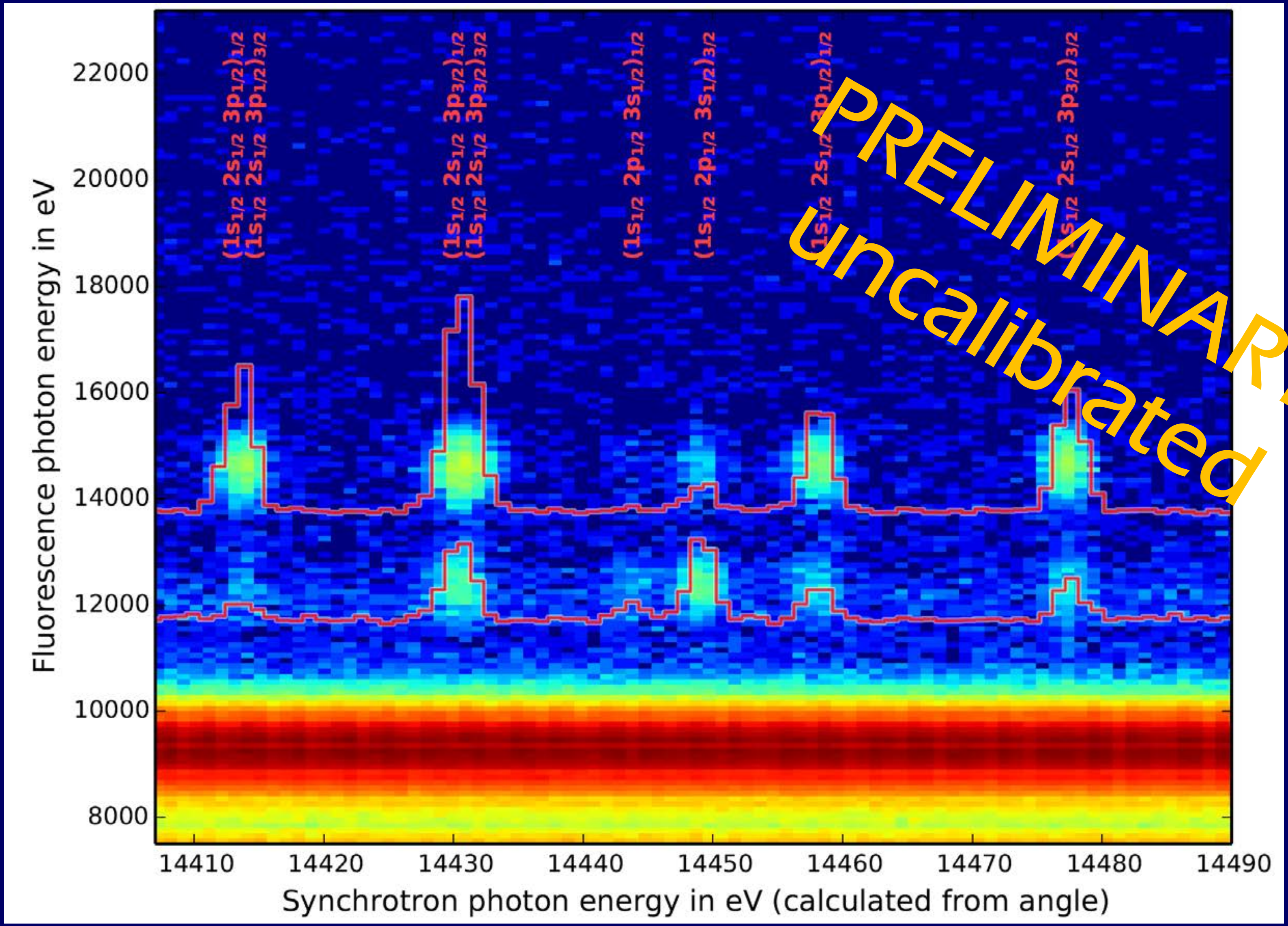
New results: Overview spectra of Br^{33+} (Li-like)



S. Bernitt, MPIK (2016)

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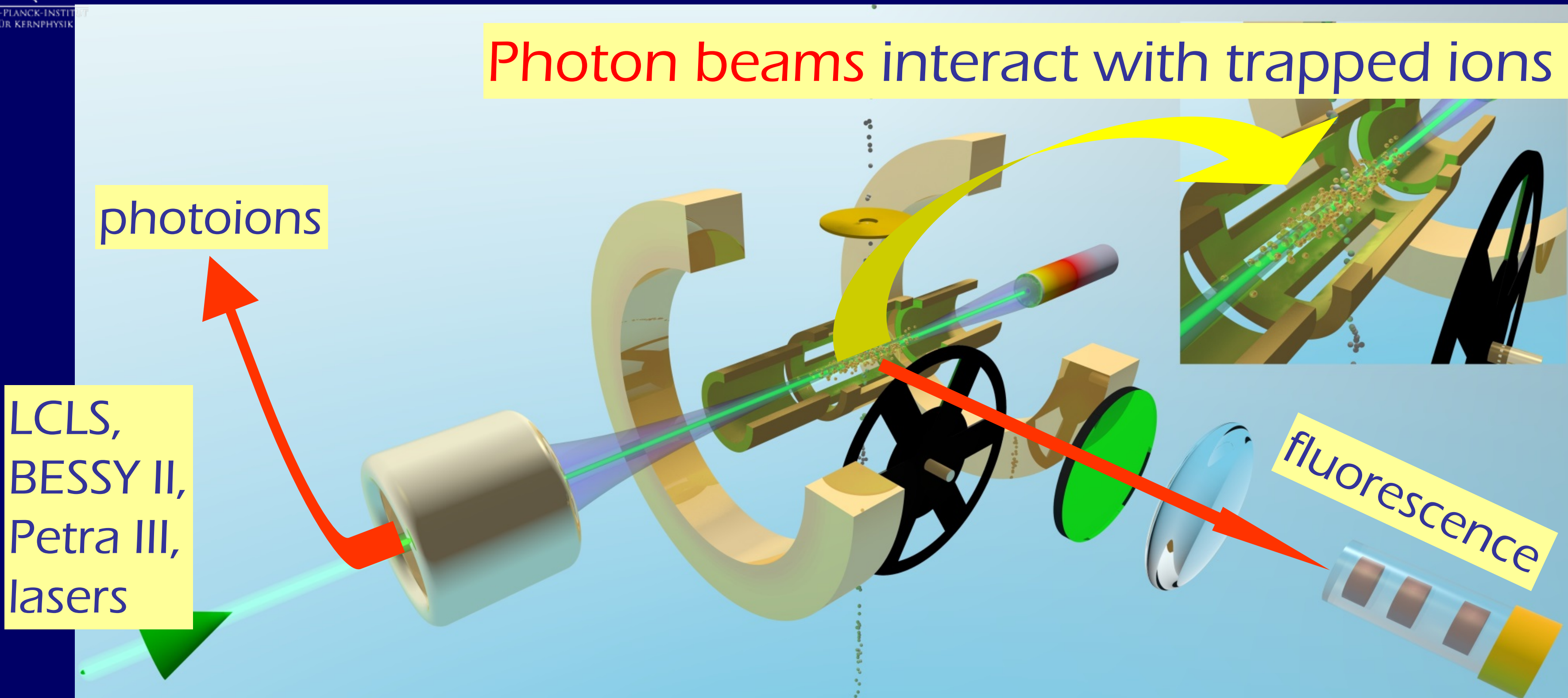
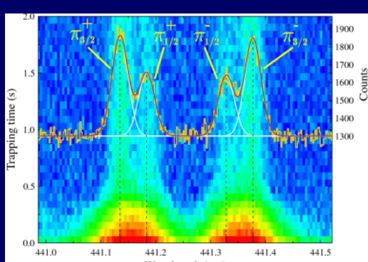
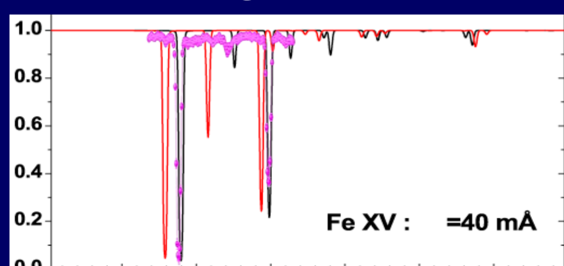
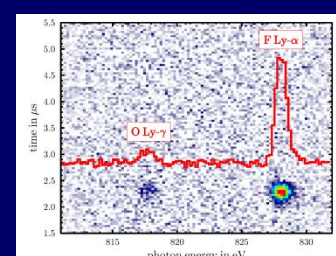
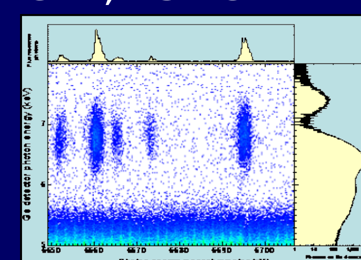
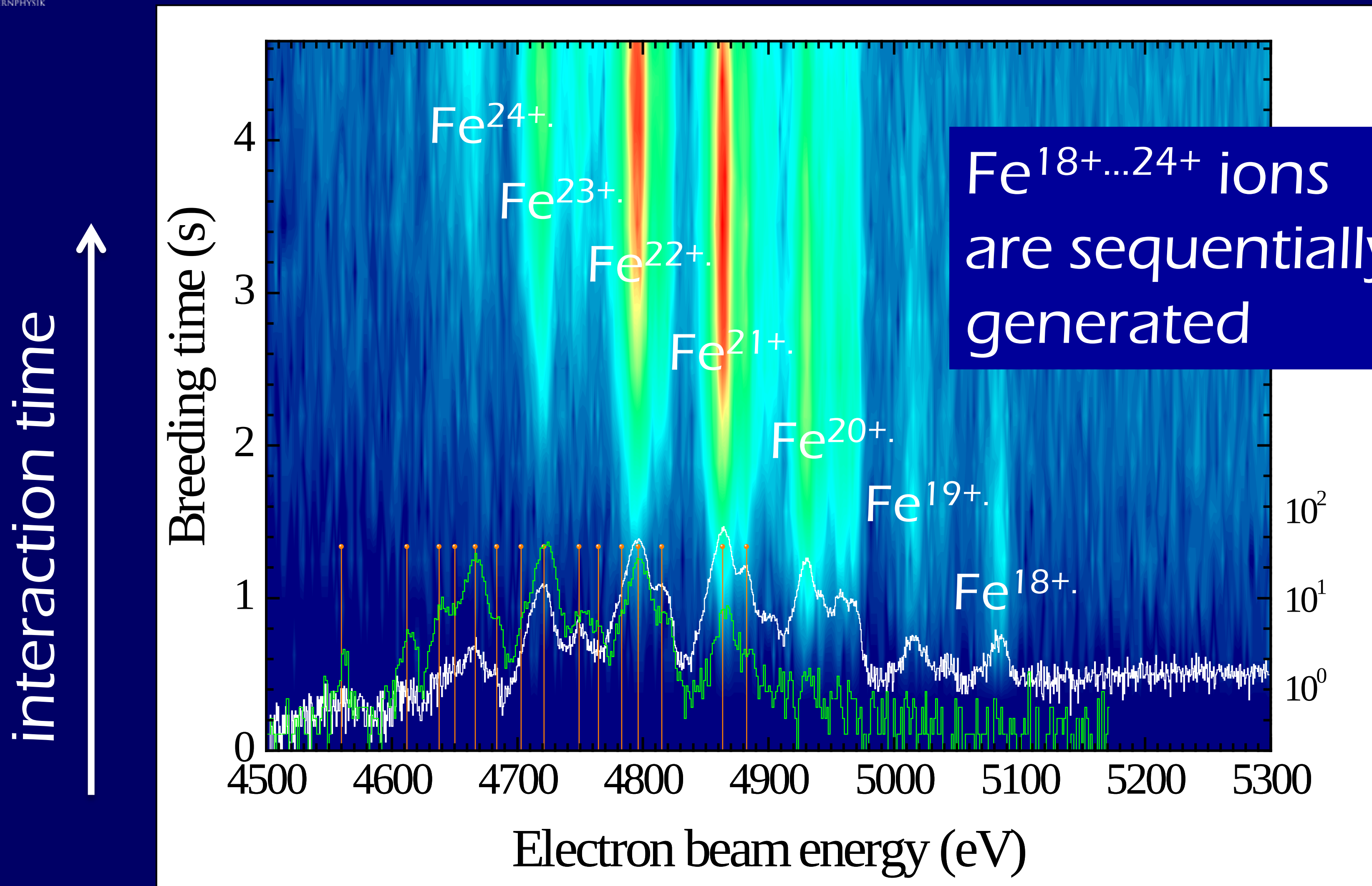
Resonant photon excitation in EBITs



Visible M1 Ar^{13+}	Soft X-ray photoionization Fe^{14+}	FEL 800 eV Fe^{16+}	Synchrotron 6 keV Fe^{24+}, 13 keV Kr^{34+}
			
V. Mäckel et al., PRL **107** 143002 (2011)	M. C. Simon et al., PRL **105** 183001 (2010)	S. Bernitt et al., Nature **492**, 225 (2012)	J. Rudolph et al., PRL **111**, 103002 (2013)

Electron-driven resonant processes

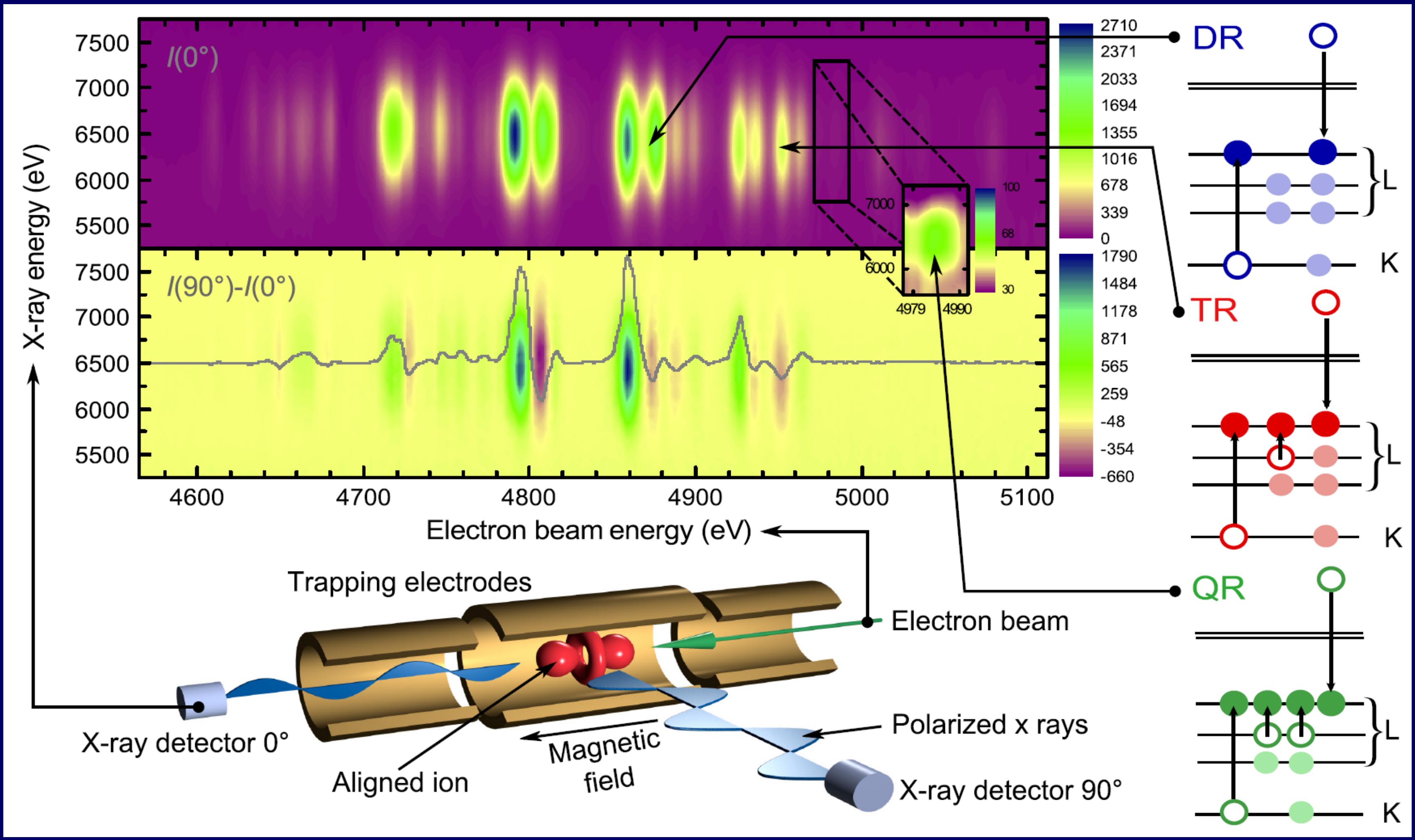
X-ray data depending on electron energy



$Fe^{18+...24+}$ ions are sequentially generated

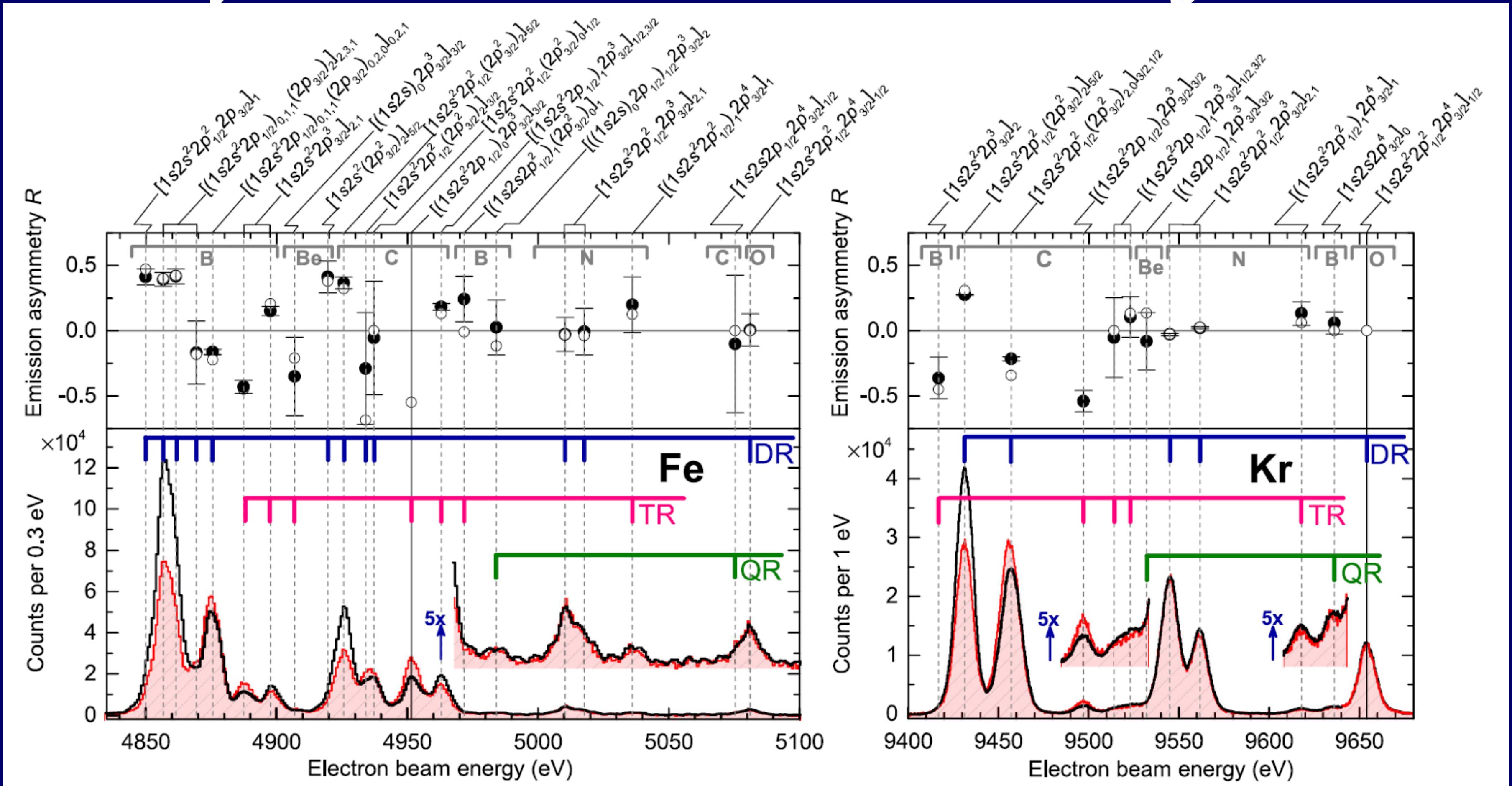
Ions in any desired charge state can be prepared, stored and spectroscopically studied

Unexpected, strong contributions by many-electron resonant excitation at high resolution



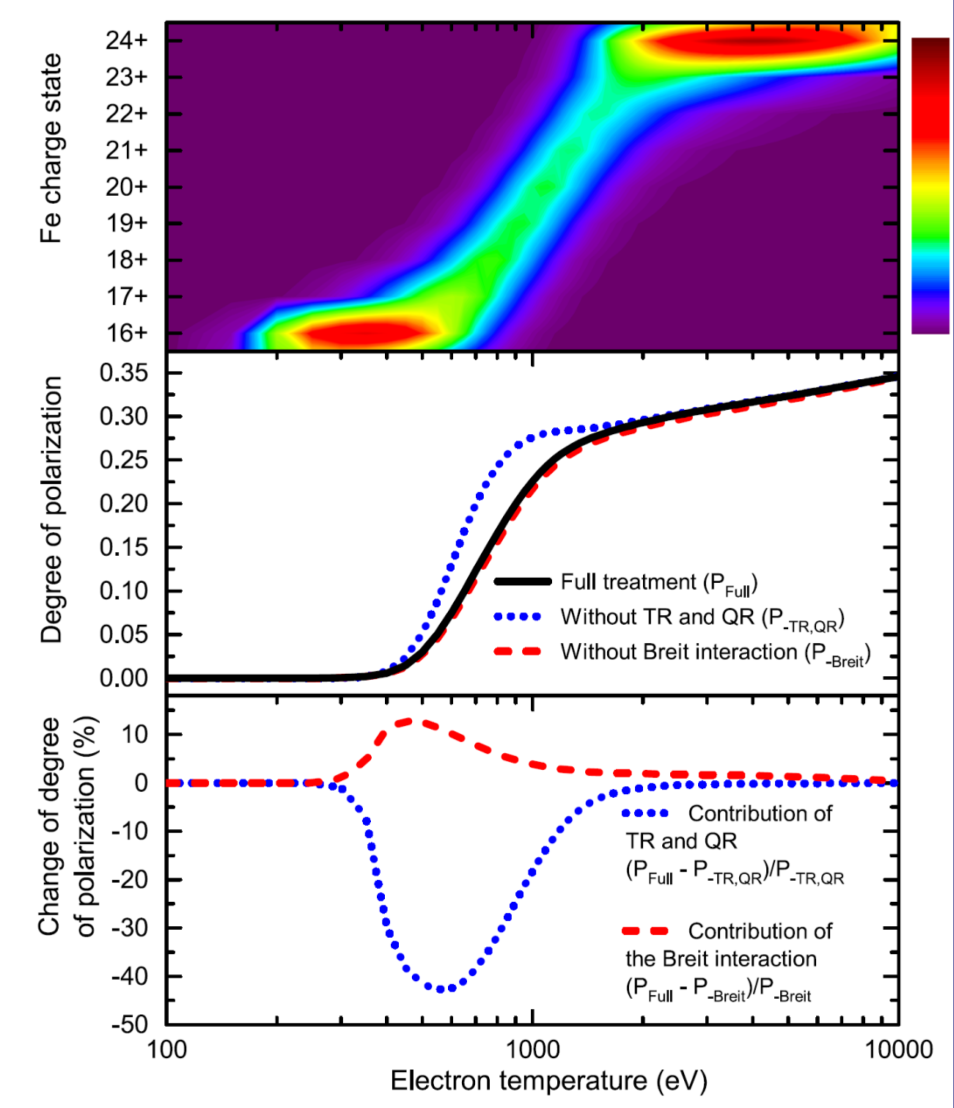
C. Shah et al., Phys. Rev. E **93**, 061201(R) (2016)
C. Beilmann et al., Phys. Rev. Lett **107**, 143201 (2011)
C. Beilmann et al., Phys. Rev. A **88**, 062706 (2013)

Unexpected, strong contributions by many-electron resonant excitation at high resolution



C. Shah et al., Phys. Rev. E **93**, 061201(R) (2016)
C. Beilmann et al., Phys. Rev. Lett **107**, 143201 (2011)
C. Beilmann et al., Phys. Rev. A **88**, 062706 (2013)

Mean charge state of plasmas changed by many-electron resonant excitation



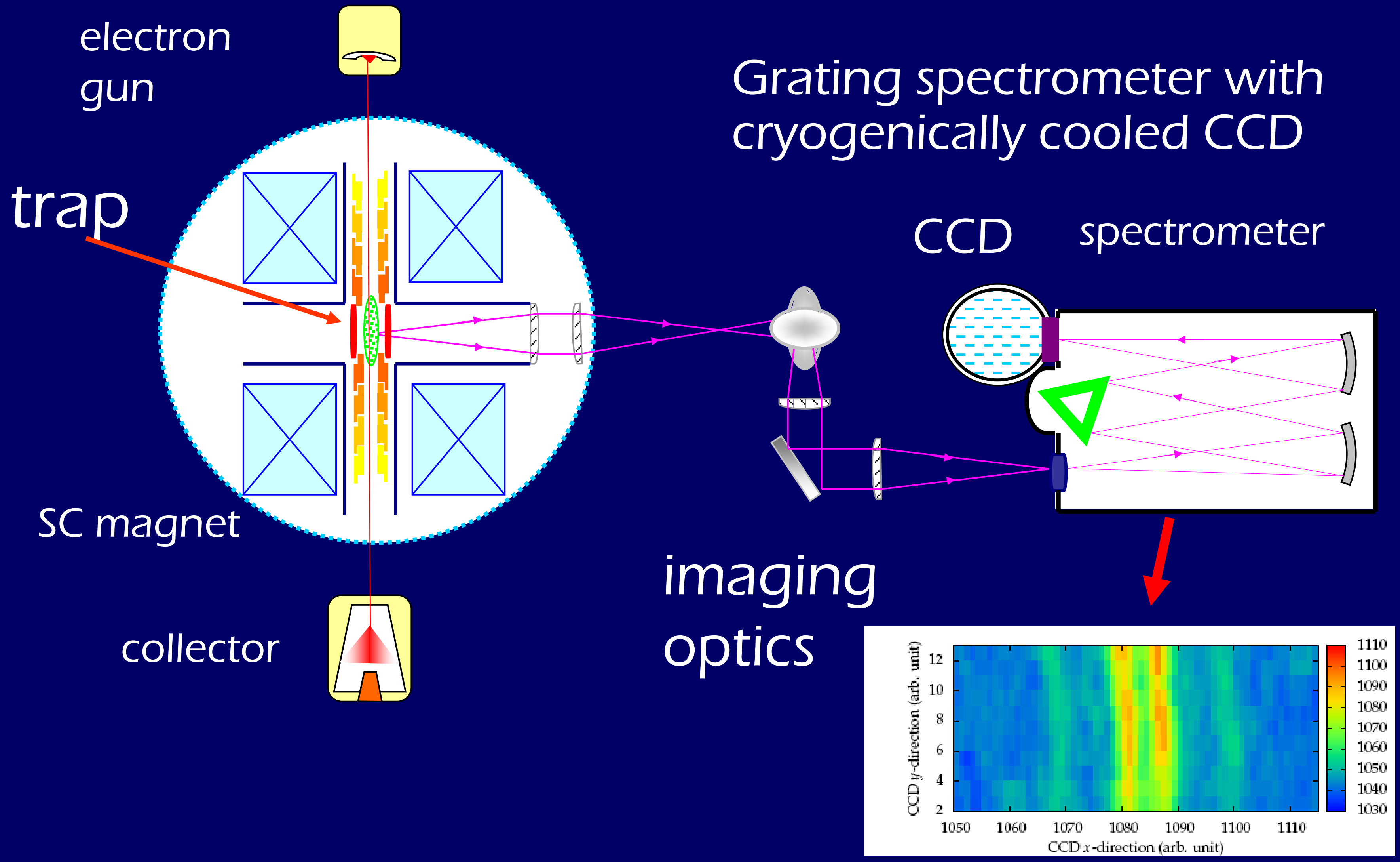
C. Shah et al., Phys. Rev. E **93**, 061201(R) (2016)

Conclusions from FEL, synchrotron and photorecombination studies

- Previously known but neglected complex multielectron processes have experimentally shown unexpectedly strong contributions to both photrecombination and photoionization
- Inclusion of those channels in calculations is necessary to achieve agreement with existing experimental data
- Even the most advanced theoretical methods are not as accurate as the experiments
- Achieving agreement at the 1% (energies) respectively 5% (cross sections) levels will require more dedicated theoretical work and benchmarking experimental data

Optical and EUV spectroscopy with EBITs

Spectroscopy of few-electron ions in the visible range



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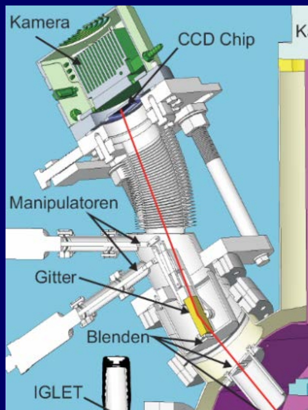
Electron beam ion trap diagnostics

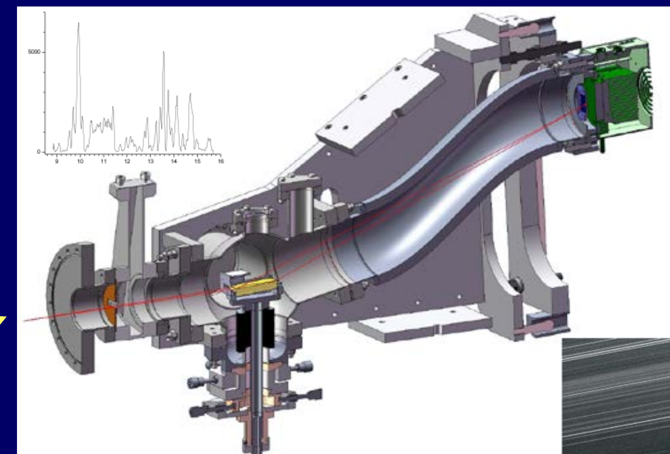


EUV grating spectrometer 1

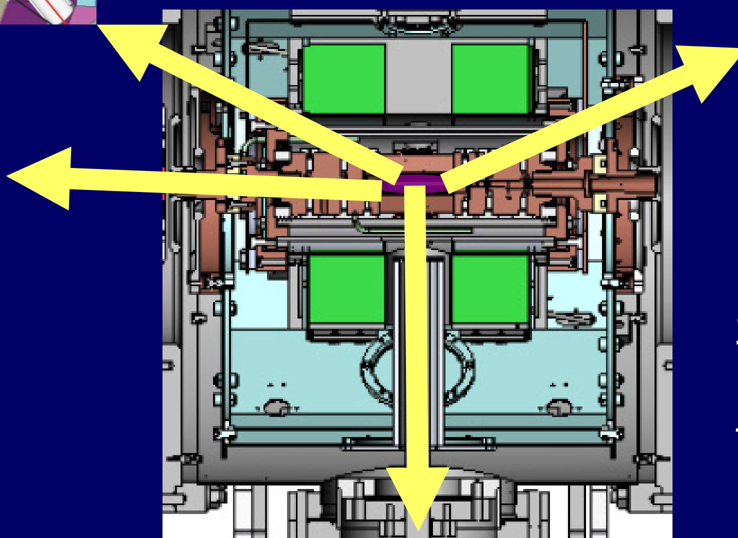
EUV to soft X-ray

EUV grating spectrometer 2

EUV



X-ray



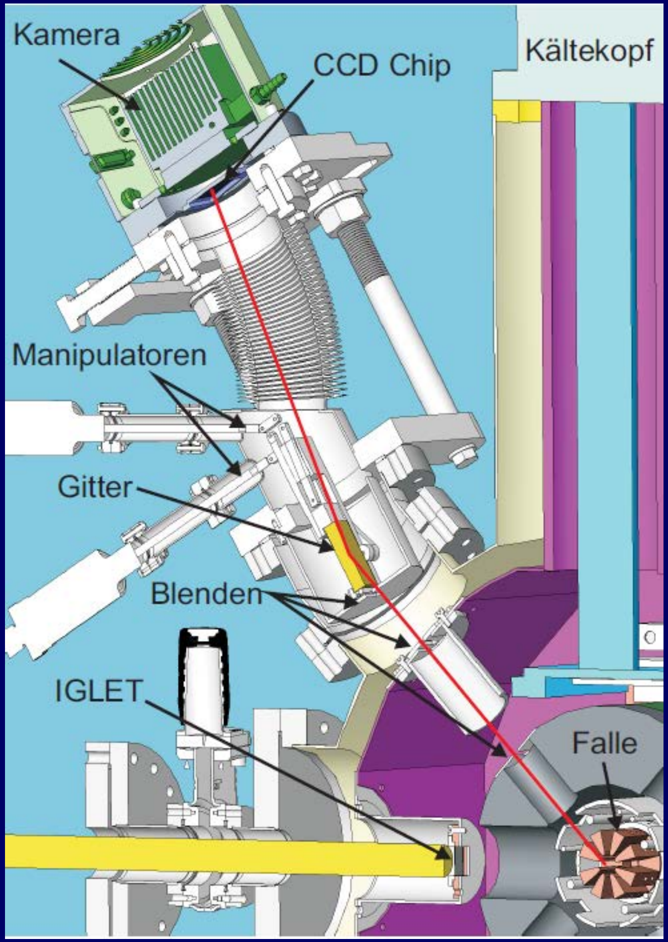
X-ray
Silicon drift detector
Germanium detector

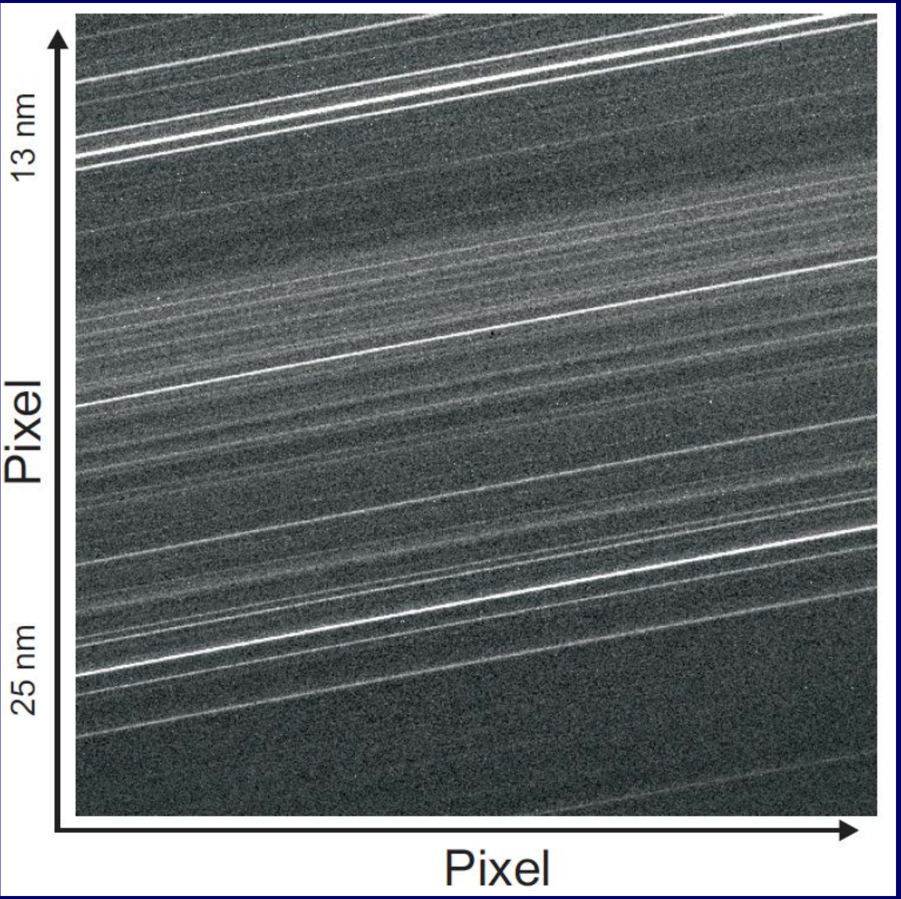
Si drift detector, Ge detector
- X-ray photons 1 to 30 keV

Two grating spectrometers
- EUV photons 40 eV to 1 keV

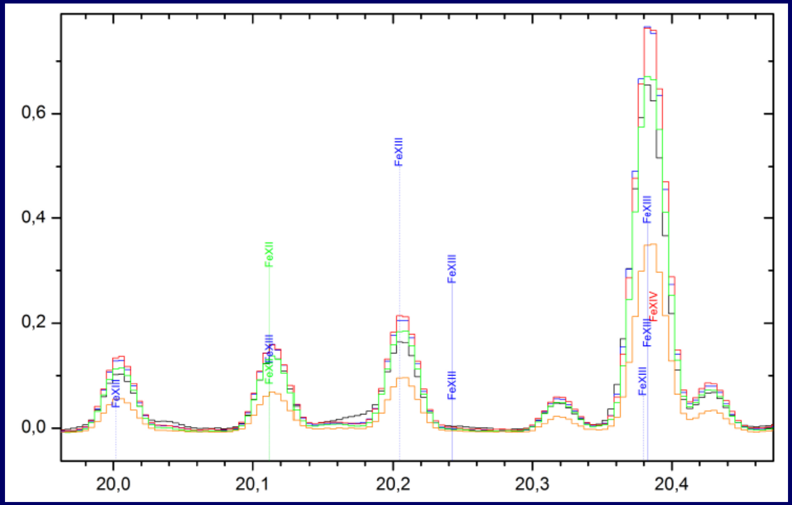
Metallic magnetic microcalorimeter
- X-ray photons 2 to 8 keV

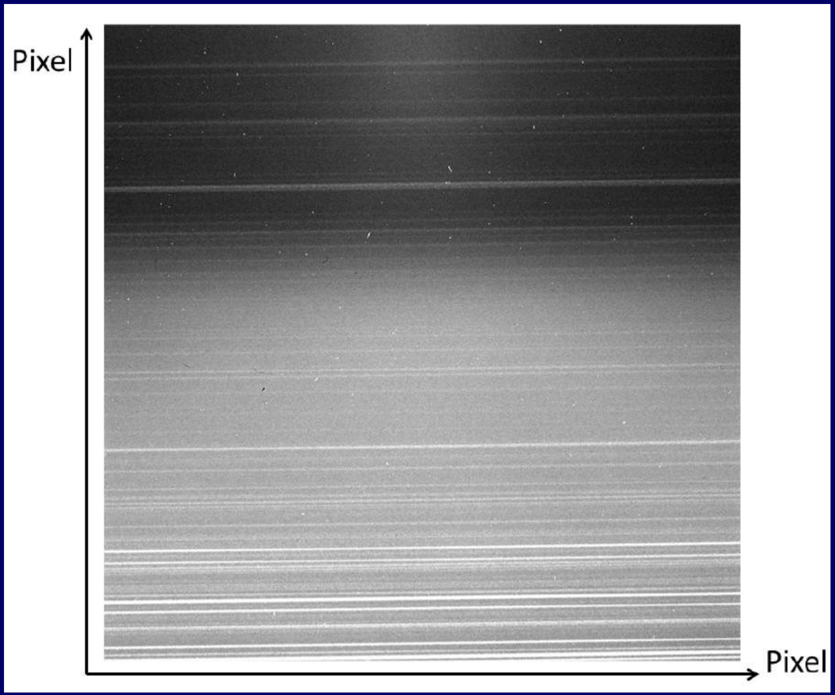
EUV diagnostics

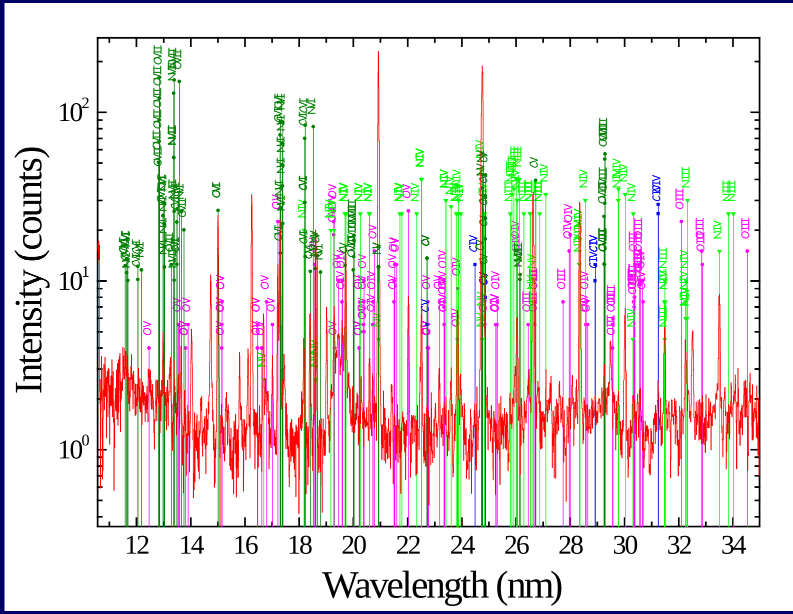




EUV diagnostics

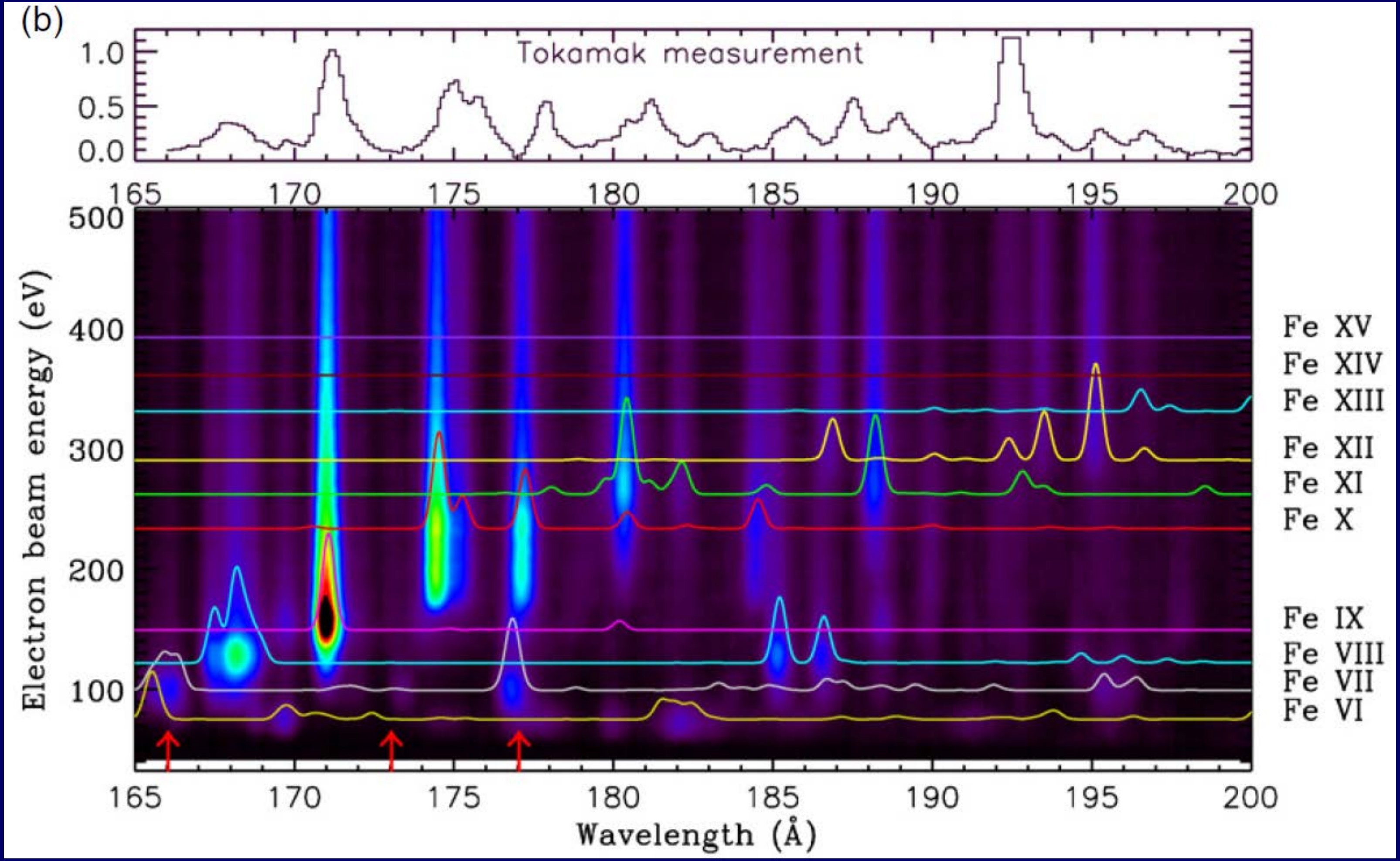






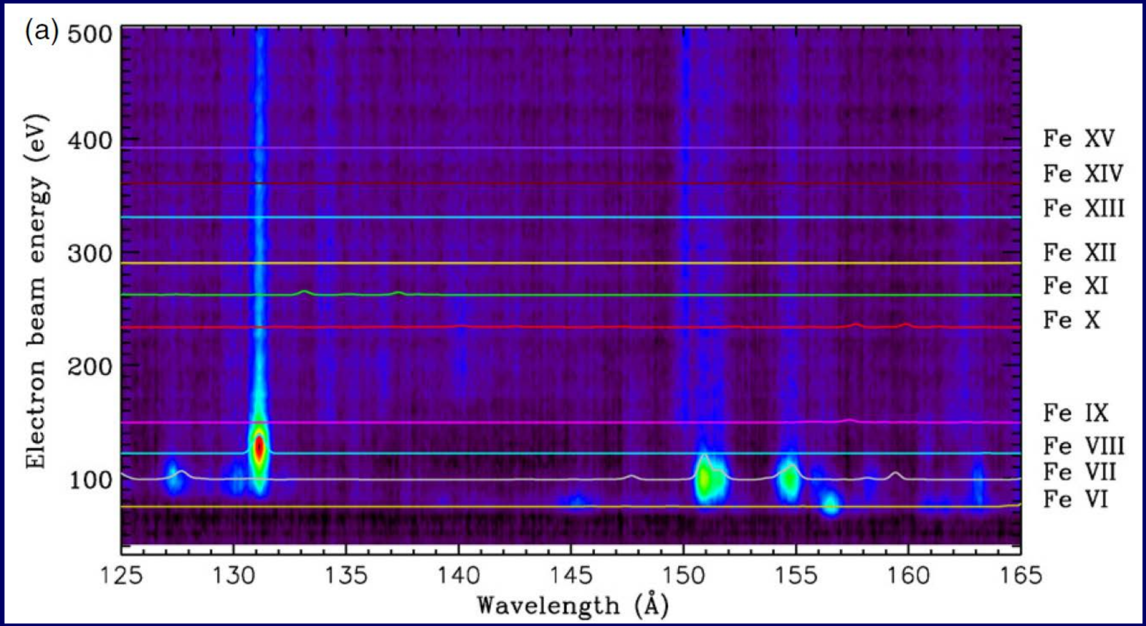
Calibration
lines of O and N

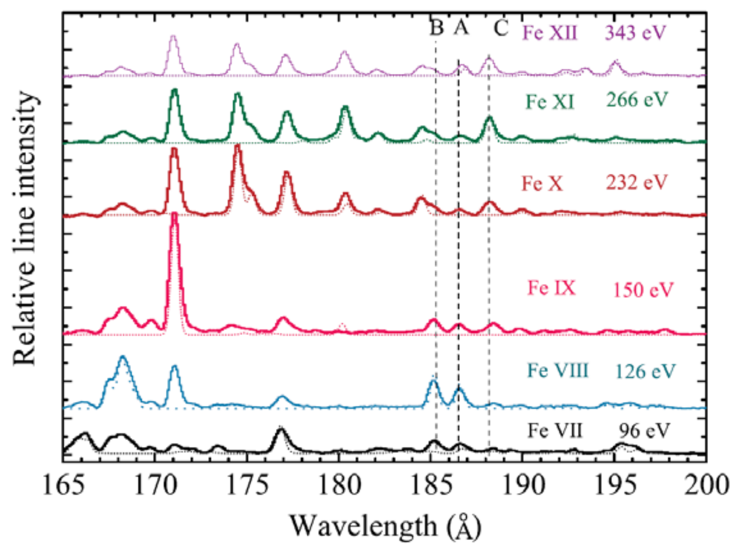
Studies of Fe HCI with charge-state resolution



Gu et al., Astrophys. J. 696, 2275 (2009)

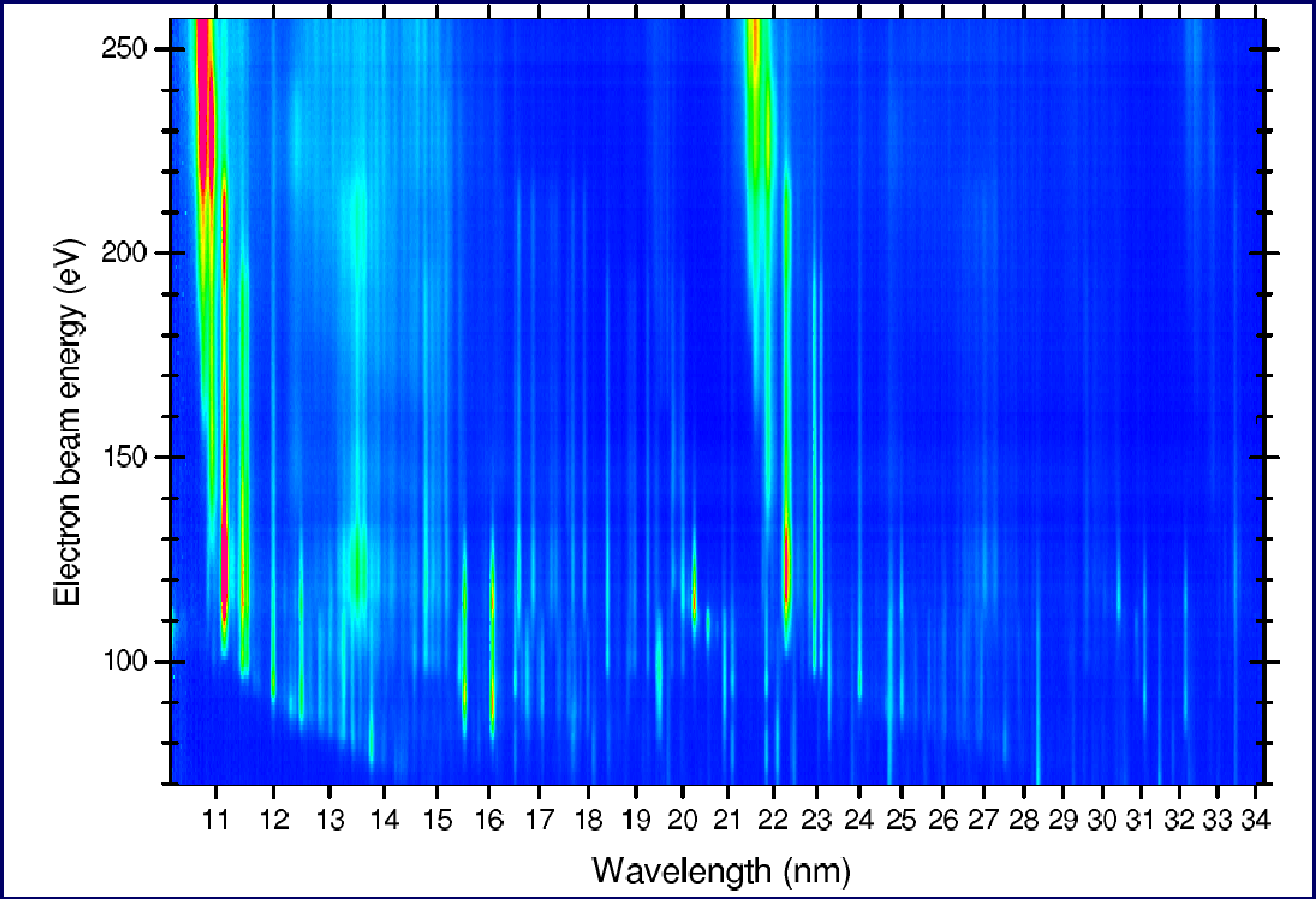
Studies of Fe HCI with charge-state resolution



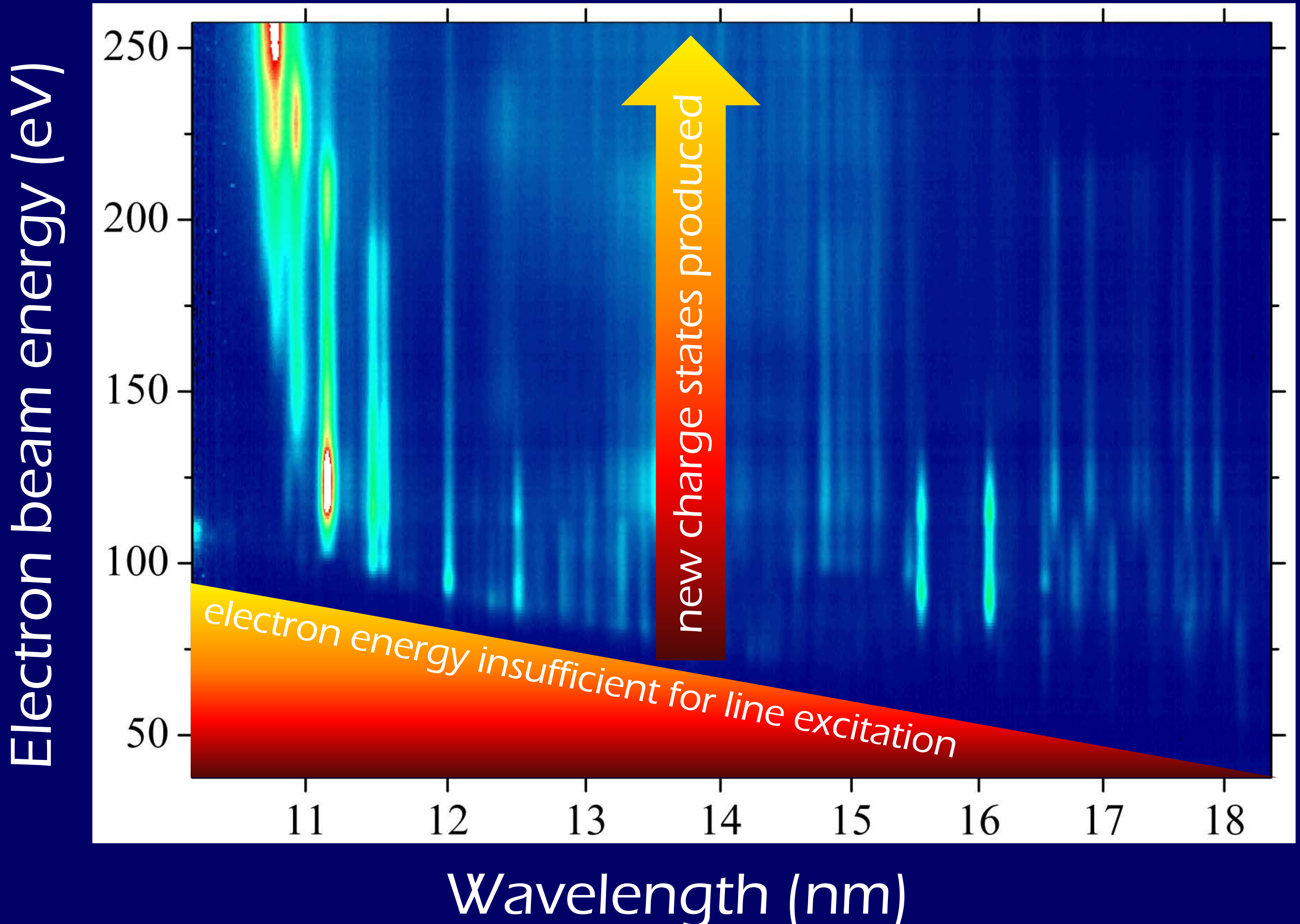


Gu et al., Astrophys. J. 696, 2275 (2009)

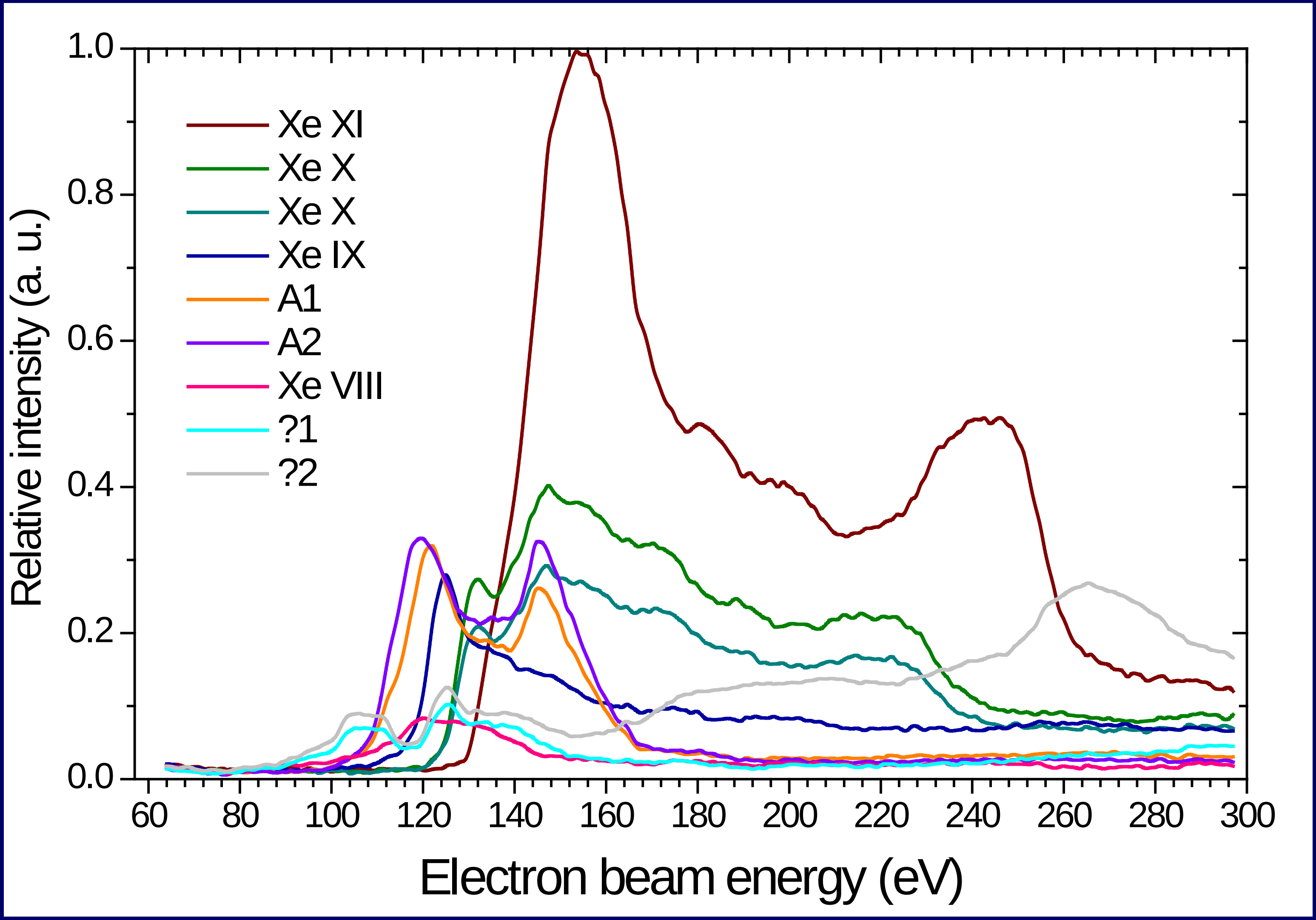
Charge state resolved spectra of Xe



Charge state resolved spectra of Xe

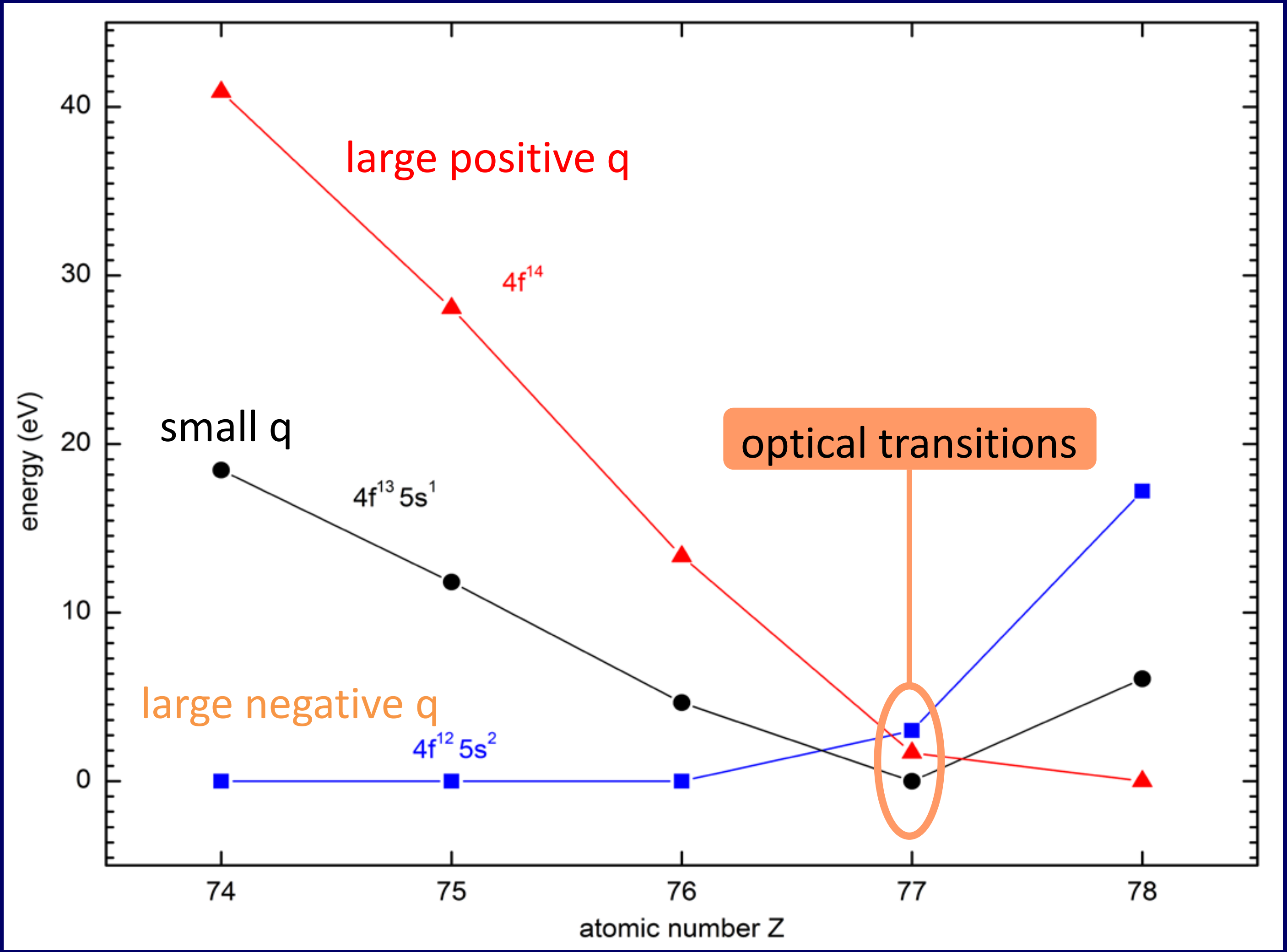


Excitation yield vs. electron beam energy



Metastable-aided electron-impact ionization (MAEII)

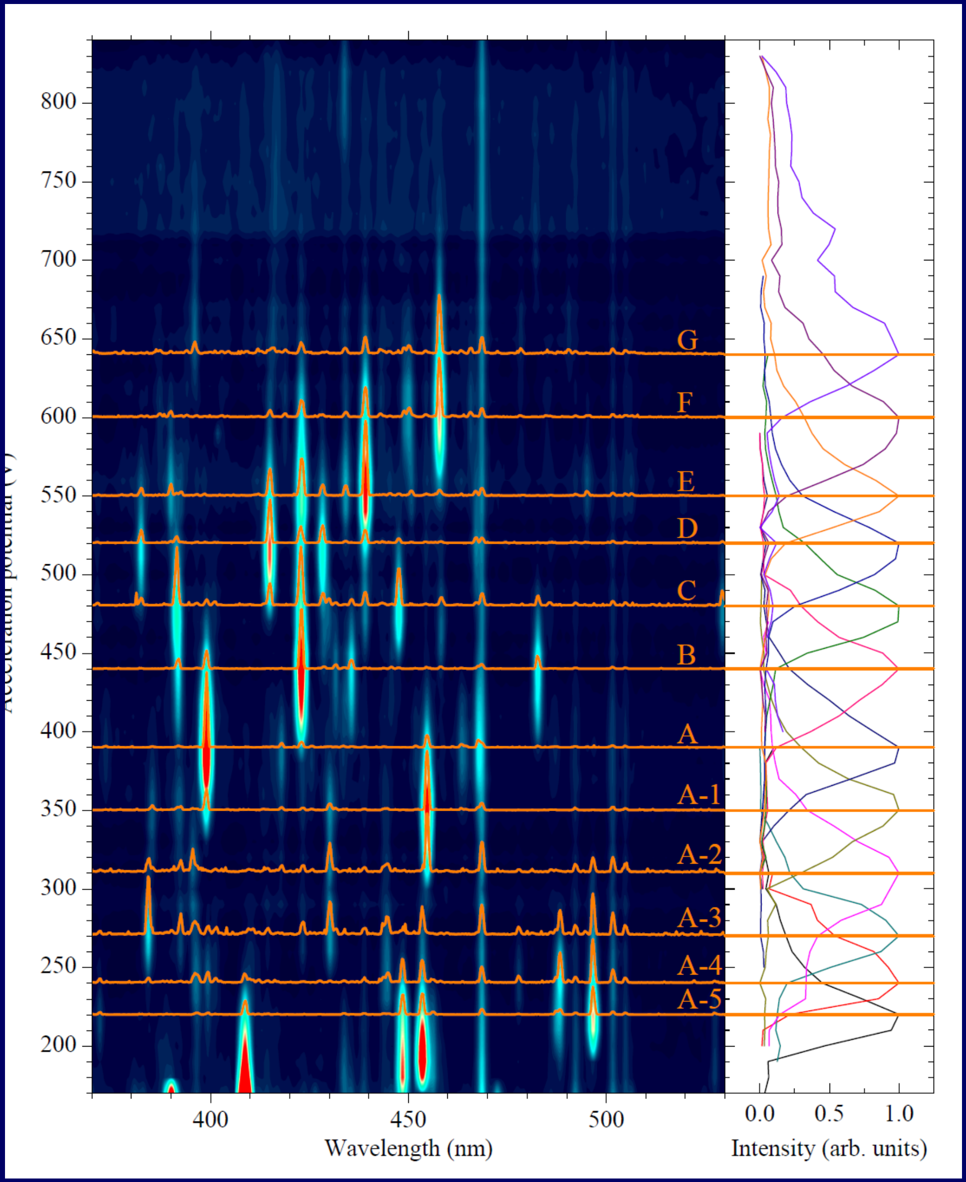
Level crossings in Ir^{17+} for α-clock



Ir^{17+}: q ~ 740 000 cm^{-1} ⟺ Hg^{+}: q ~ 52 200 cm^{-1}

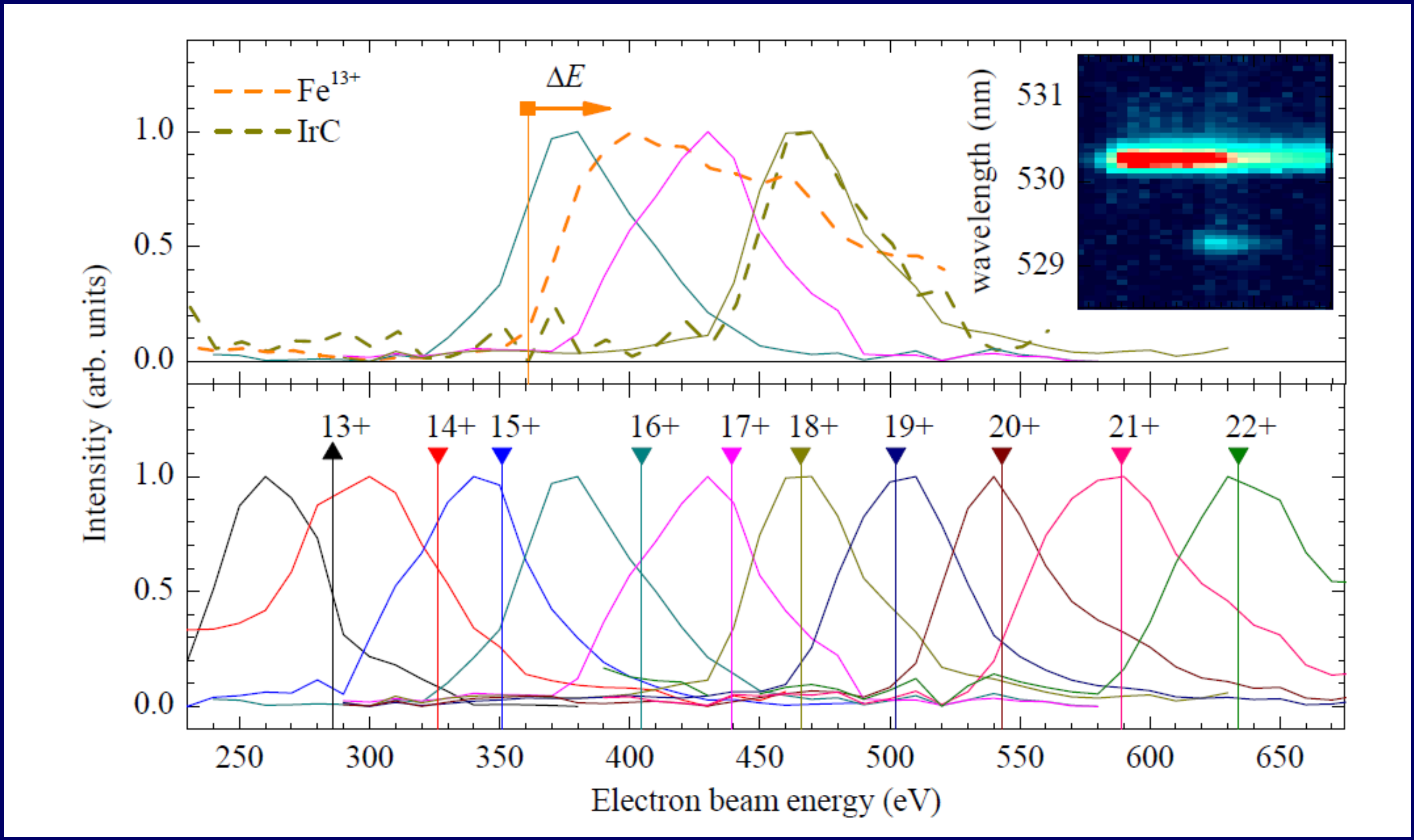
Predictions: J. C. Berengut *et al.*, PRL **106**, 210802 (2011)

Level crossings at Ir^{17+} provide α sensitivity



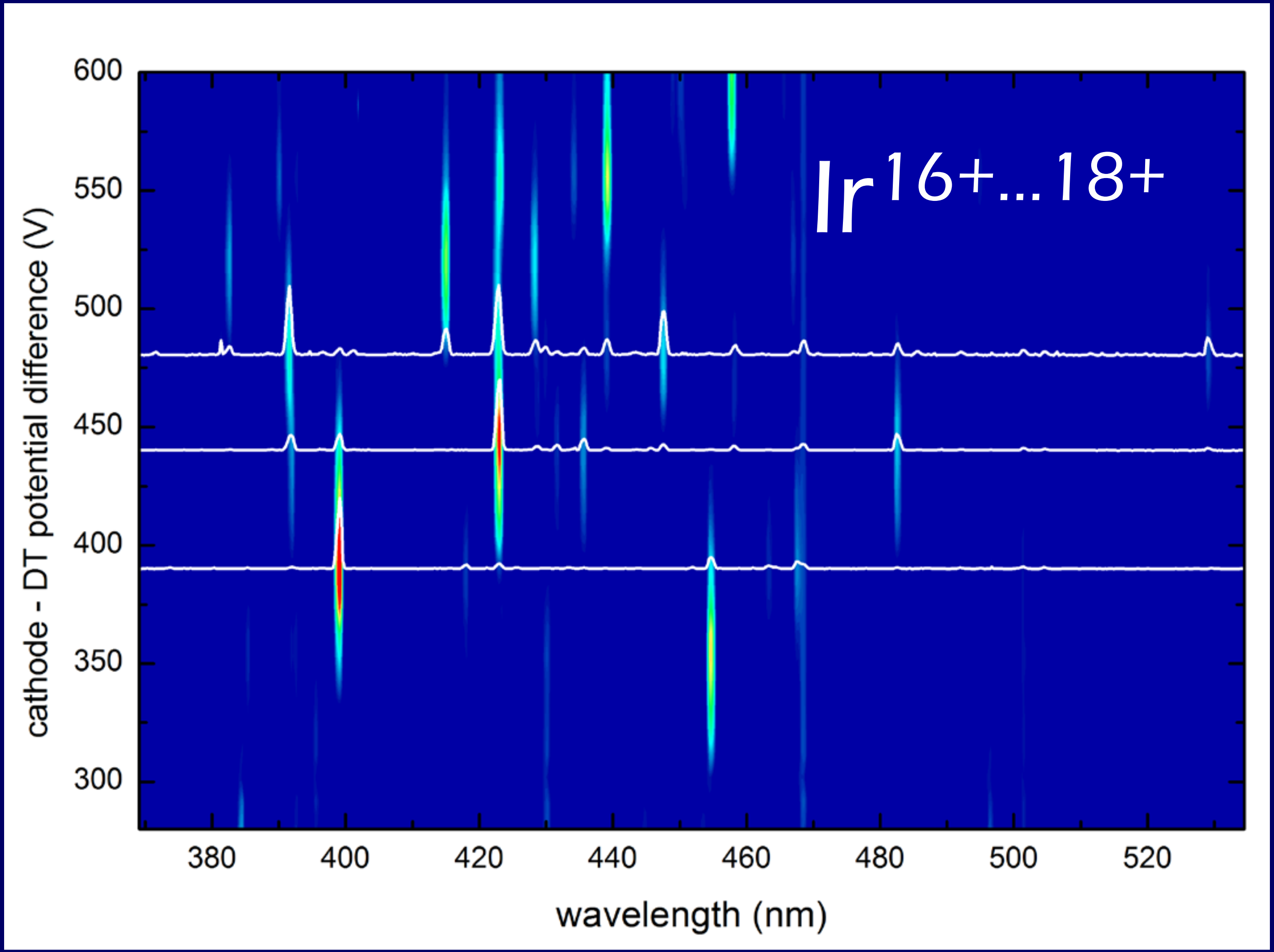
- With increasing charge state, reordering of levels takes place
- 4f levels go below 5s at Z≈77 (Berengut *PRL* 2011)
- Levels of opposite parity cross: $4f^{12}\ 5s^2$, $4f^{13}\ 5^s$, $4f^{14}$
- M1, E1, E2, M2, M3 transitions become possible

Searching for the right charge state



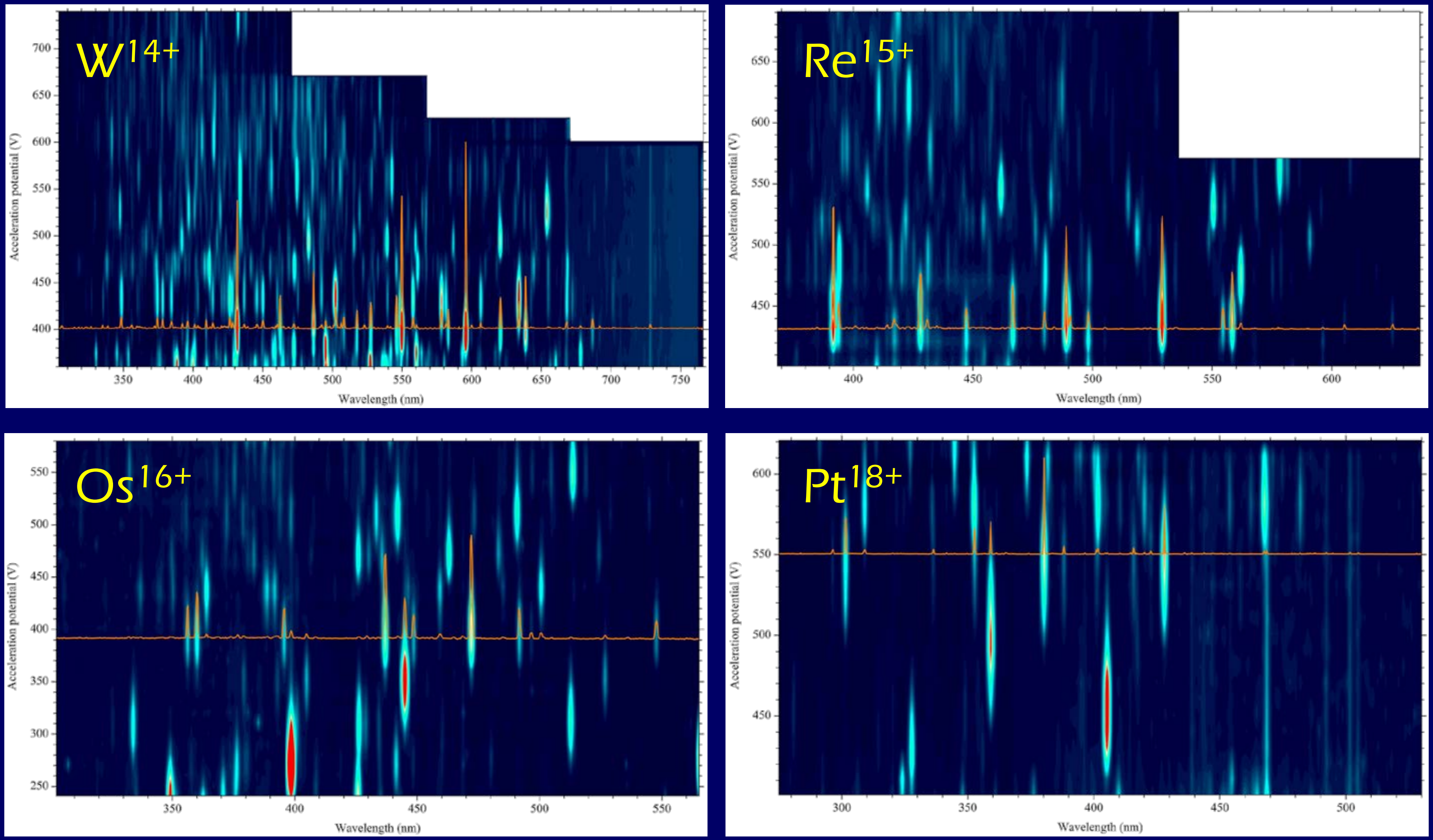
- By changing the electron beam energy, new charge states stepwise appear
- Uncertainties in both experimental threshold energy and theoretical predicitions of ionization potentials

Visible spectra of M1 lines in Ir ions



- First ever observations of such ions
- Line identification based on theory is unreliable

Optical spectral maps Nd-like ions



Isoelectronic sequence studied in detail to find analogies

Line identification through M1-scaling functions on Nd-like isoelectronic sequences

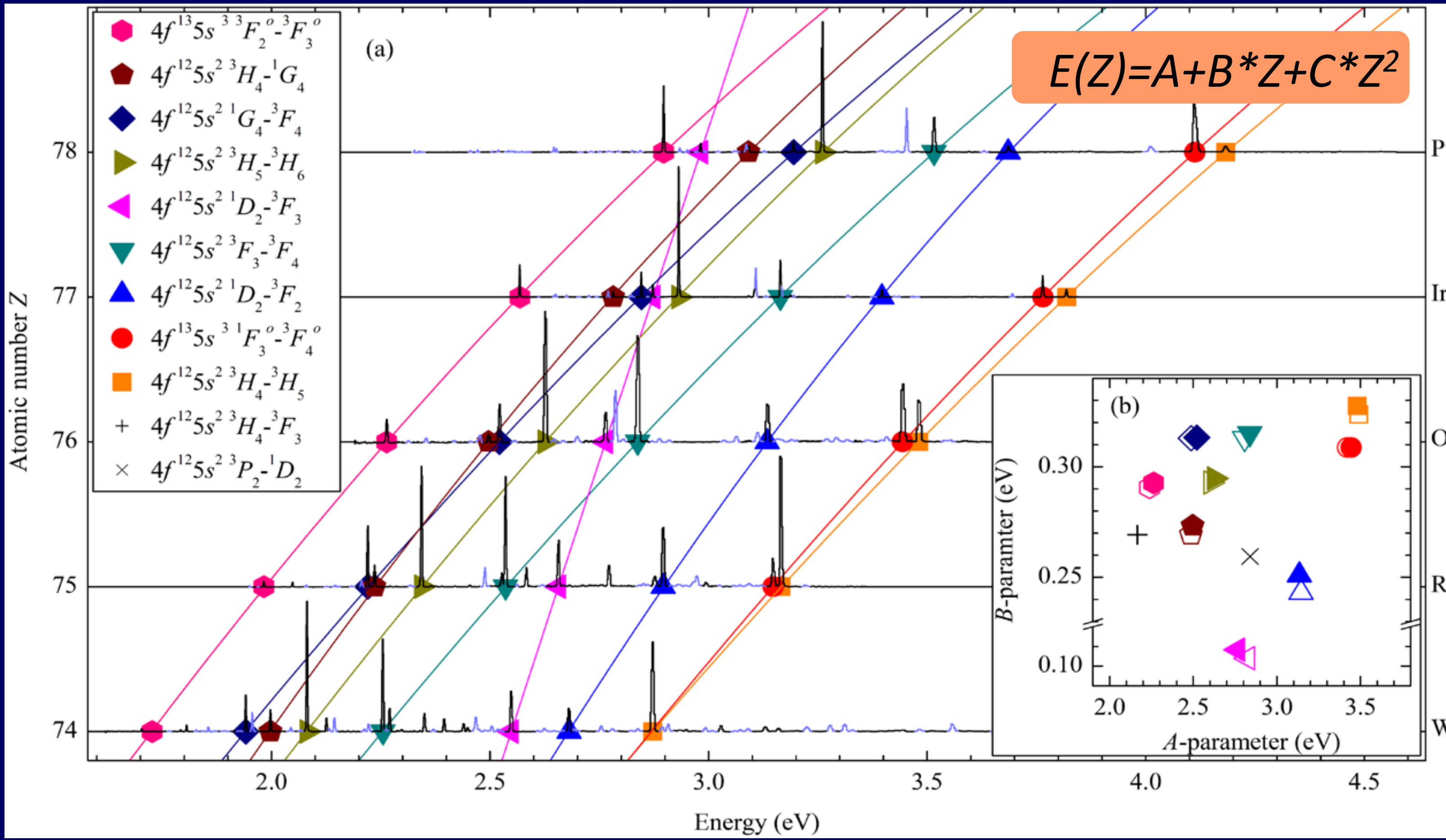
Pt

Ir

Os

Re

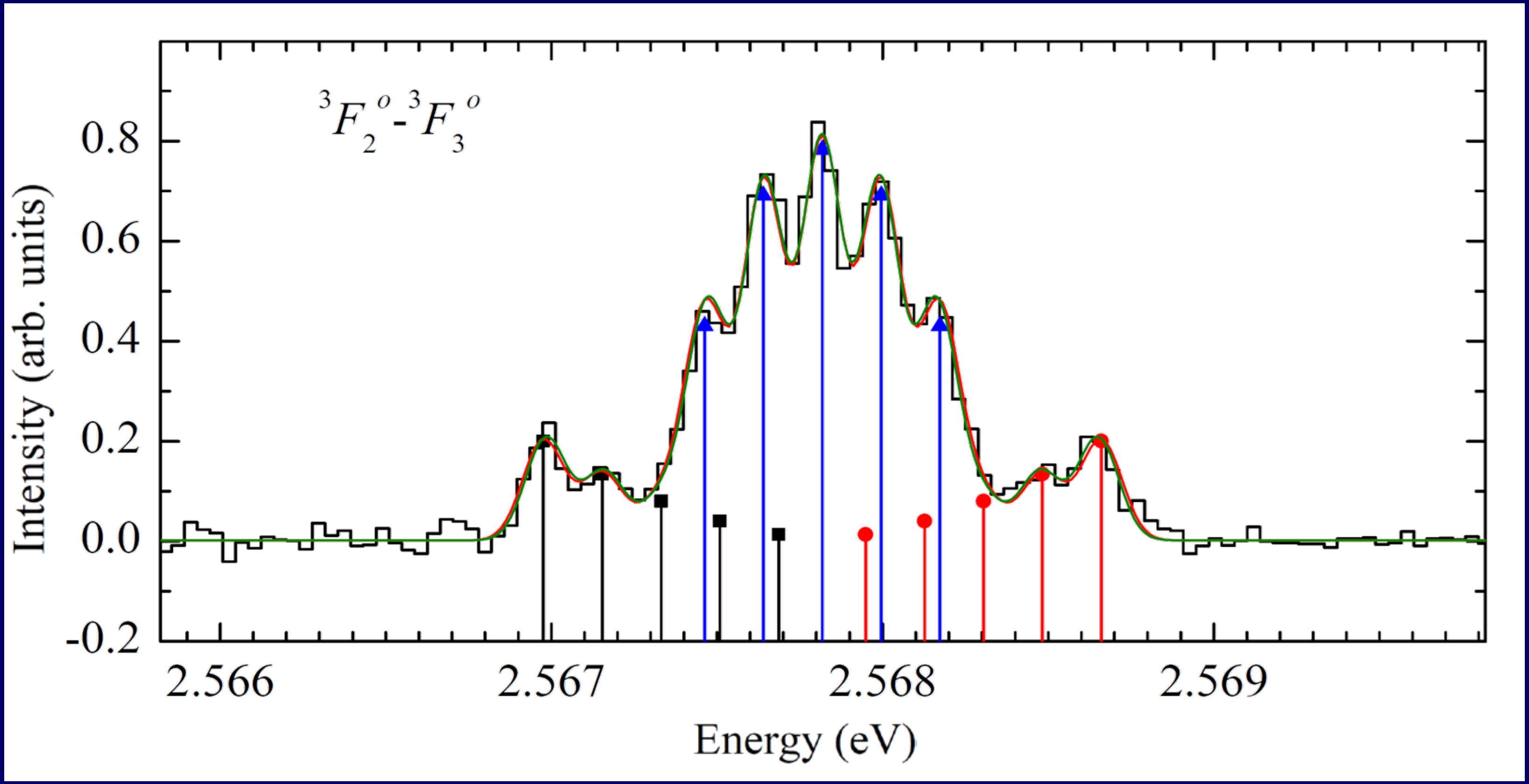
W



Comparison between theoretical and experimental scalings allow us to identify the transitions and fill the Grotrian diagram

Windberger et al., PRL **114**, 150801 (2015)

Line identification through g-factor fits

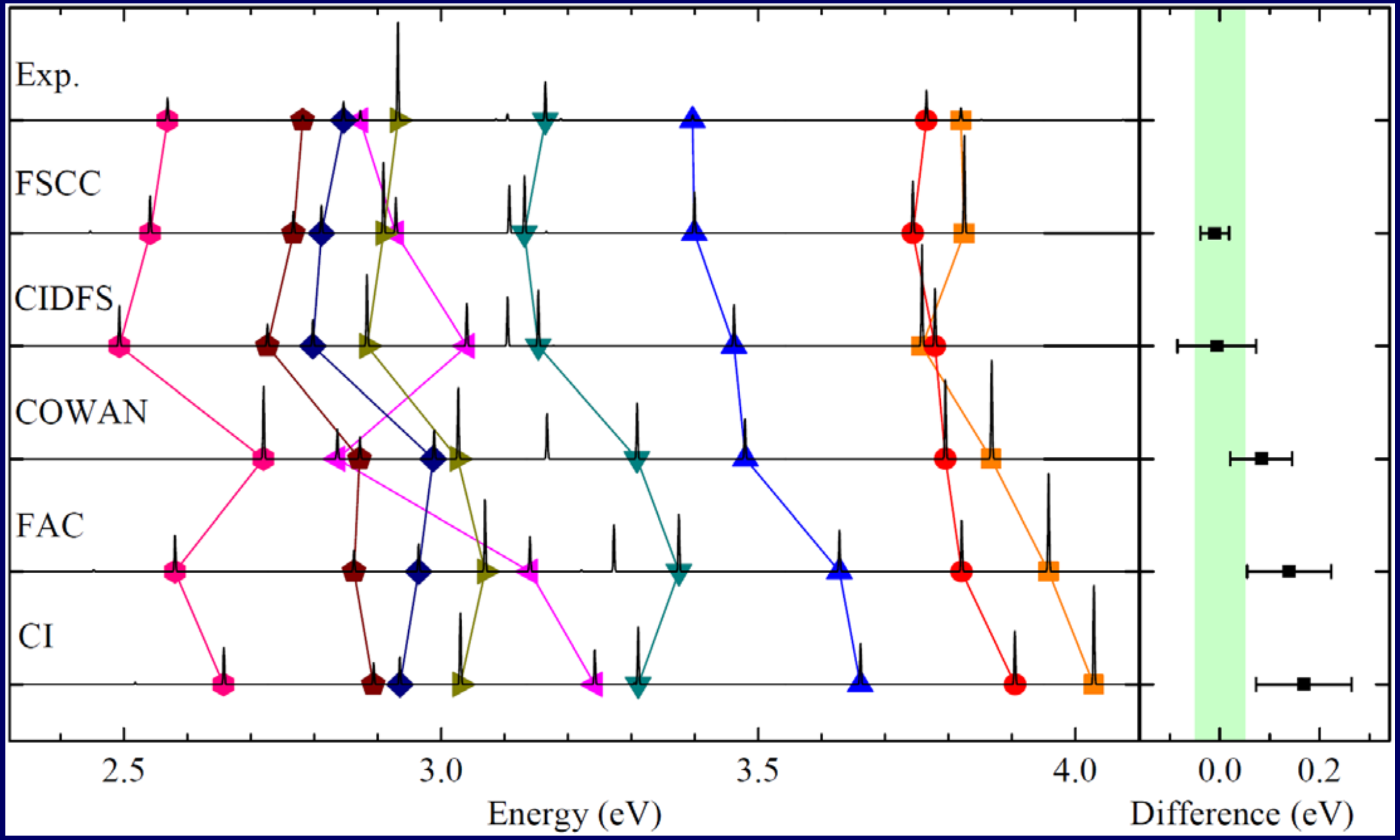


Magnetic field causes large Zeeman splitting providing an additional criterion for identification of the lines

$$\sum_{\Delta m=-1,0,1} A_{\Delta \mathrm{m}} \sum_{-J\leq m_\mathrm{J}\leq J} \langle J\ m_\mathrm{J}\ 1\ \Delta m | J'\ m_\mathrm{J}+\Delta m\rangle^2$$
$$\times\exp\left(-\frac{(E-E_0-\mu_\mathrm{B}B\,(m_\mathrm{J}\,(g-g')+\Delta m g'))^2}{2w^2}\right)$$

Windberger et al., PRL **114**, 150801 (2015)

Comparison between theories



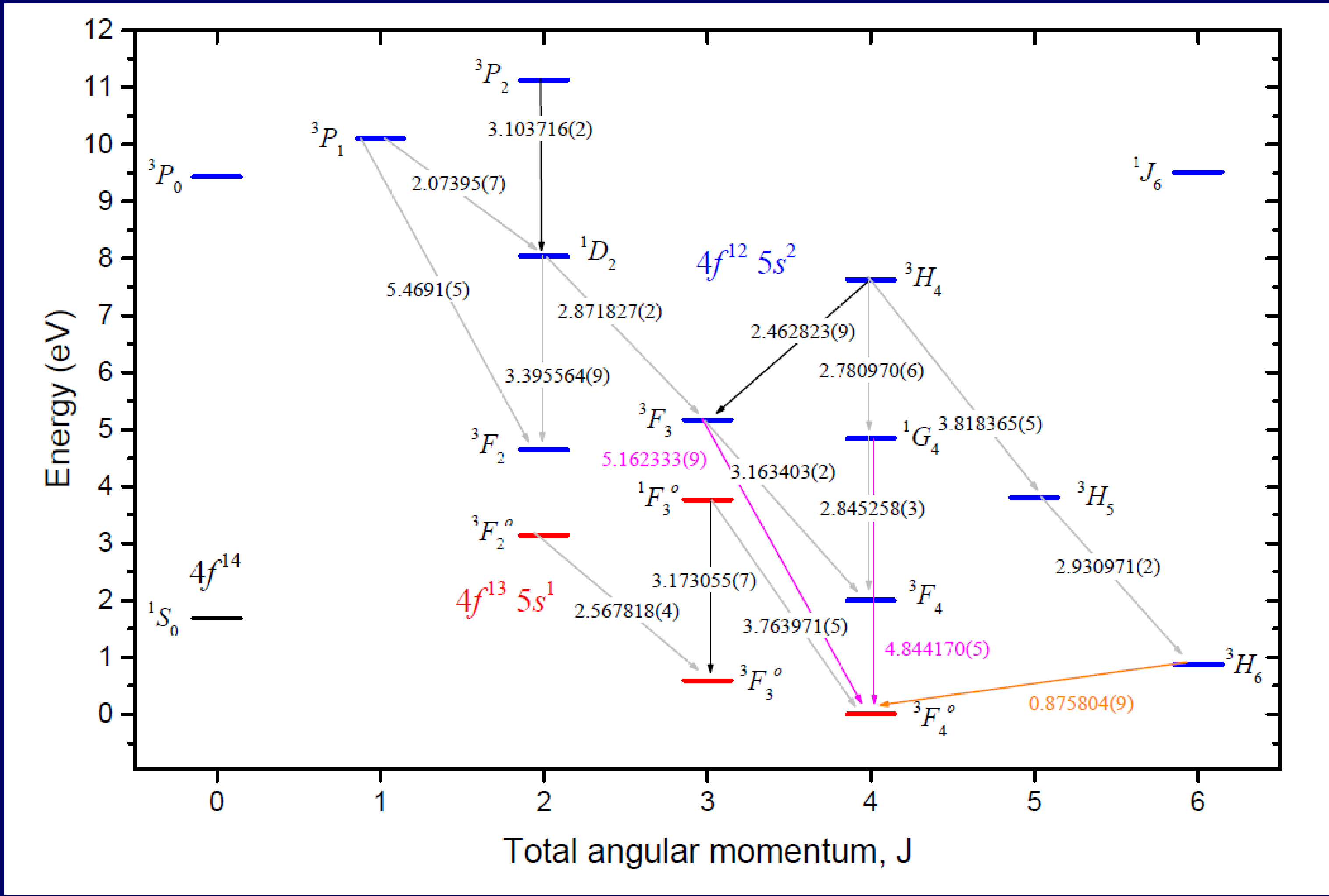
*

- Fock-space coupled cluster calculation (A. Borschevski) shows agreement with experimental result at a level suitable for identification.
- Its deviations from experiment are smaller than the average separation between spectral lines (as given by the green band).

* Berengut *et al.*, PRL **106**, (2011)

Windberger et al., PRL **114**, 150801 (2015)

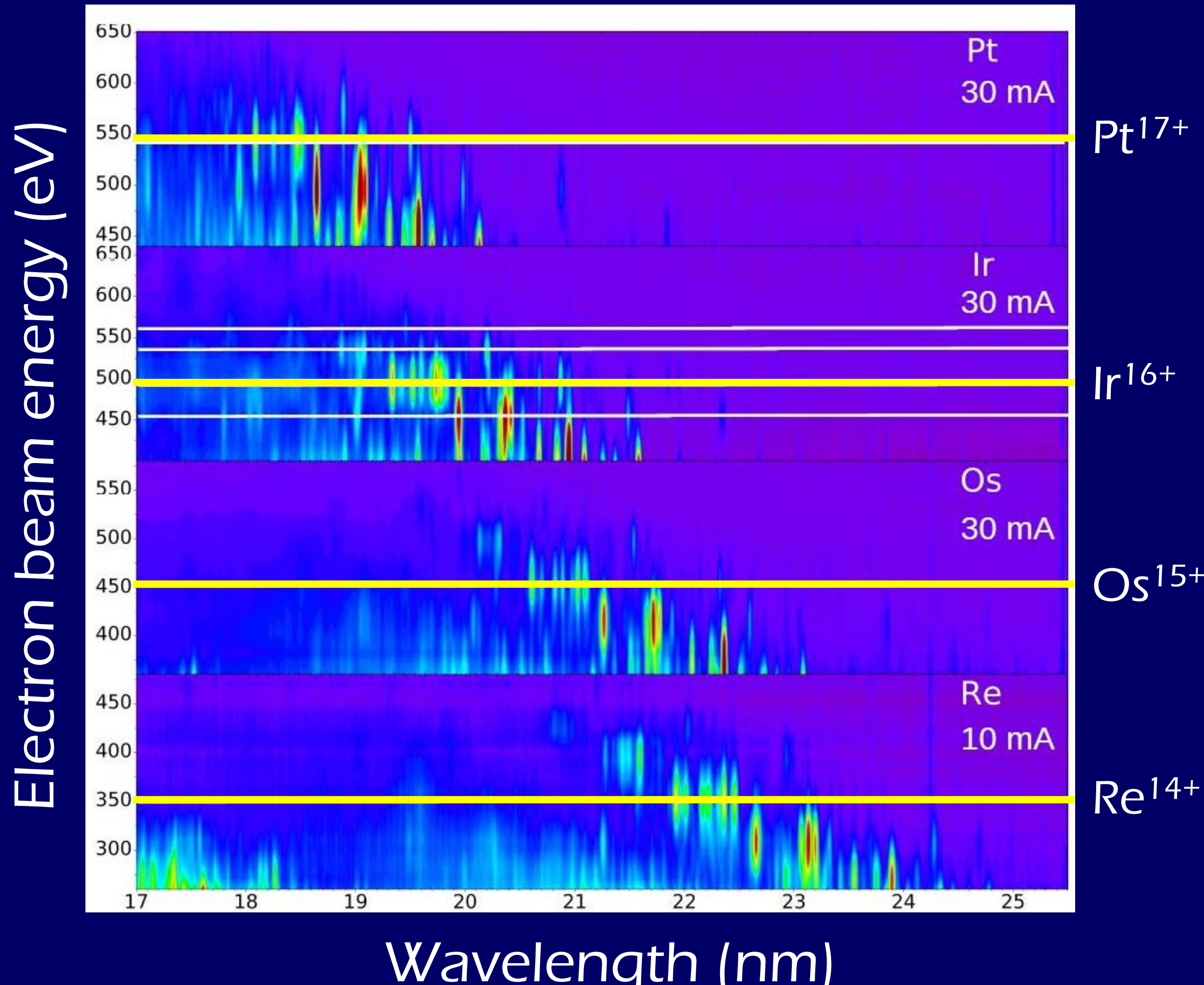
New data on $4f^{14}$, $4f^{13}5s$ and $4f^{12}5s^2$ for Ir^{17+}



Arrows: Black, identified M1 lines; magenta, tentatively identified E1; orange, inferred M2/E3 clock transition; gray , previously identified. Unconnected fine-structure levels taken from FSCC calculations.

H. Bekker, PhD thesis 2016

Pm-like (61electrons) isoelectronic sequence



Ce (Z=58)
Pr (Z=59)
Nd (Z=60)
Pm (Z=61)
Sm (Z=62)

Isoelectronic sequence studied in detail to find analogies

Understanding optical and EUV spectra of tin ions

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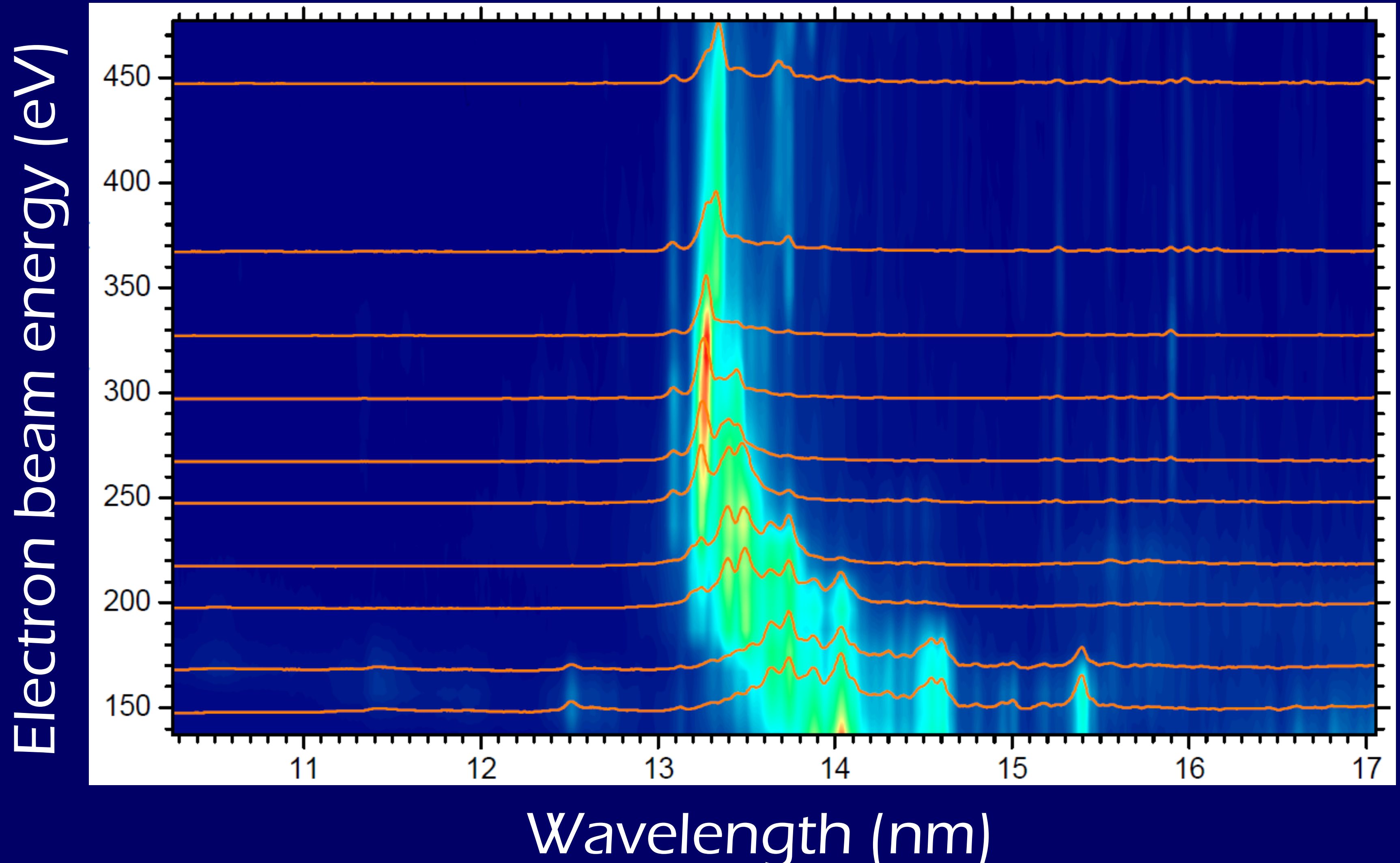
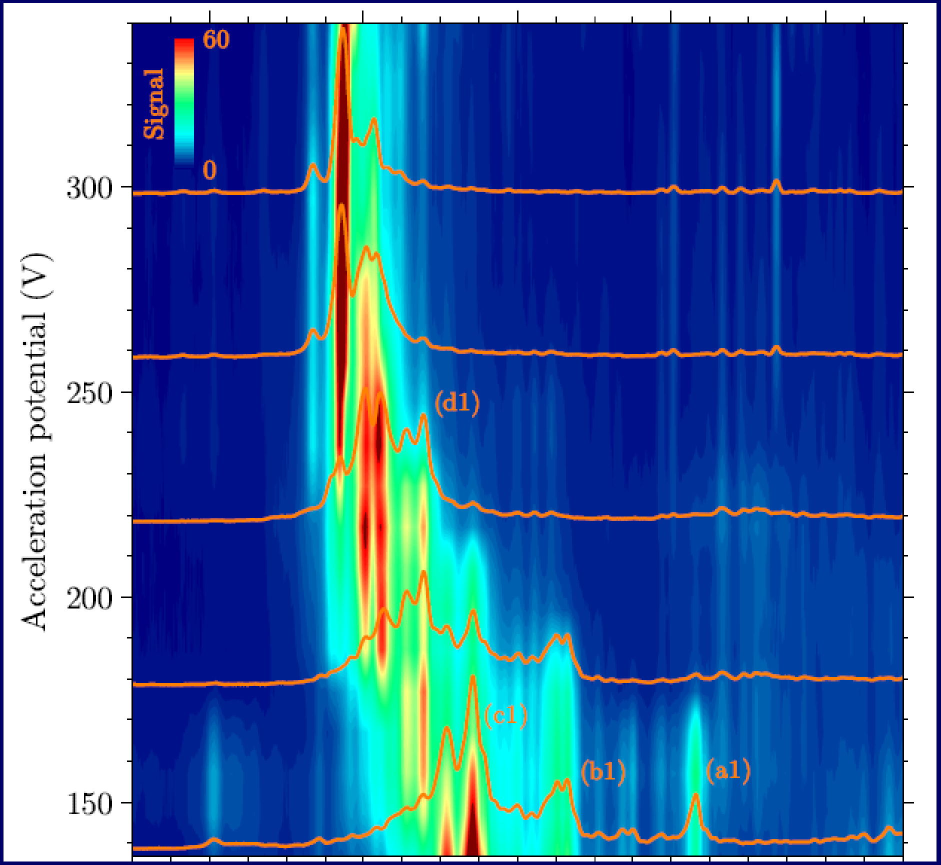
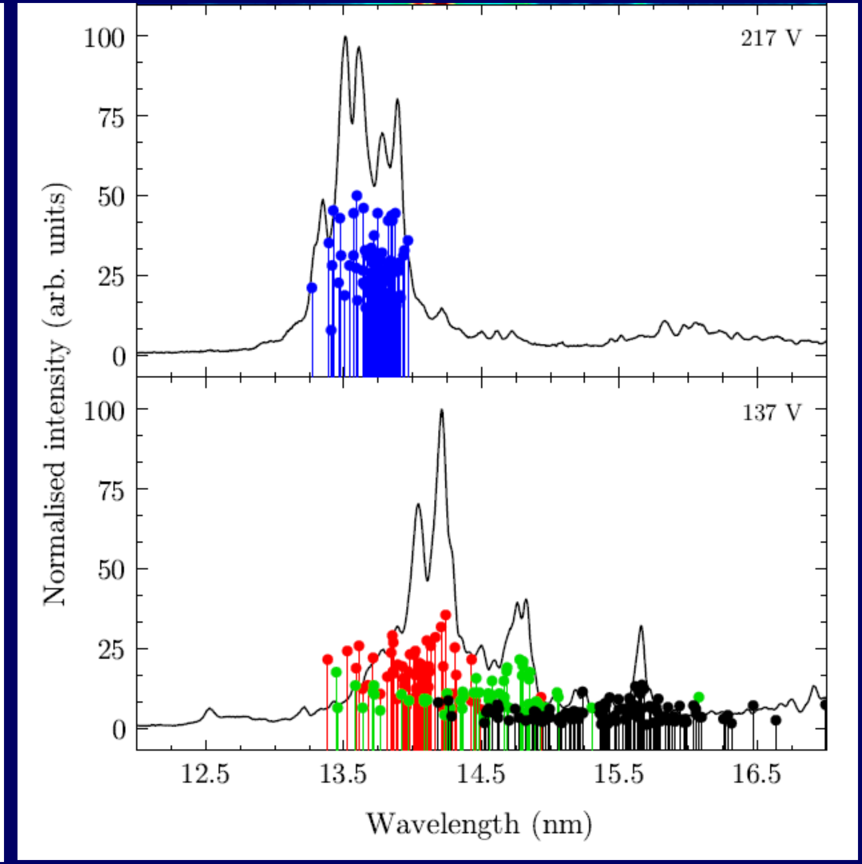
Understanding Sn spectra



H. Bekker et al., J. Phys. B **48**, 144018 (2015)

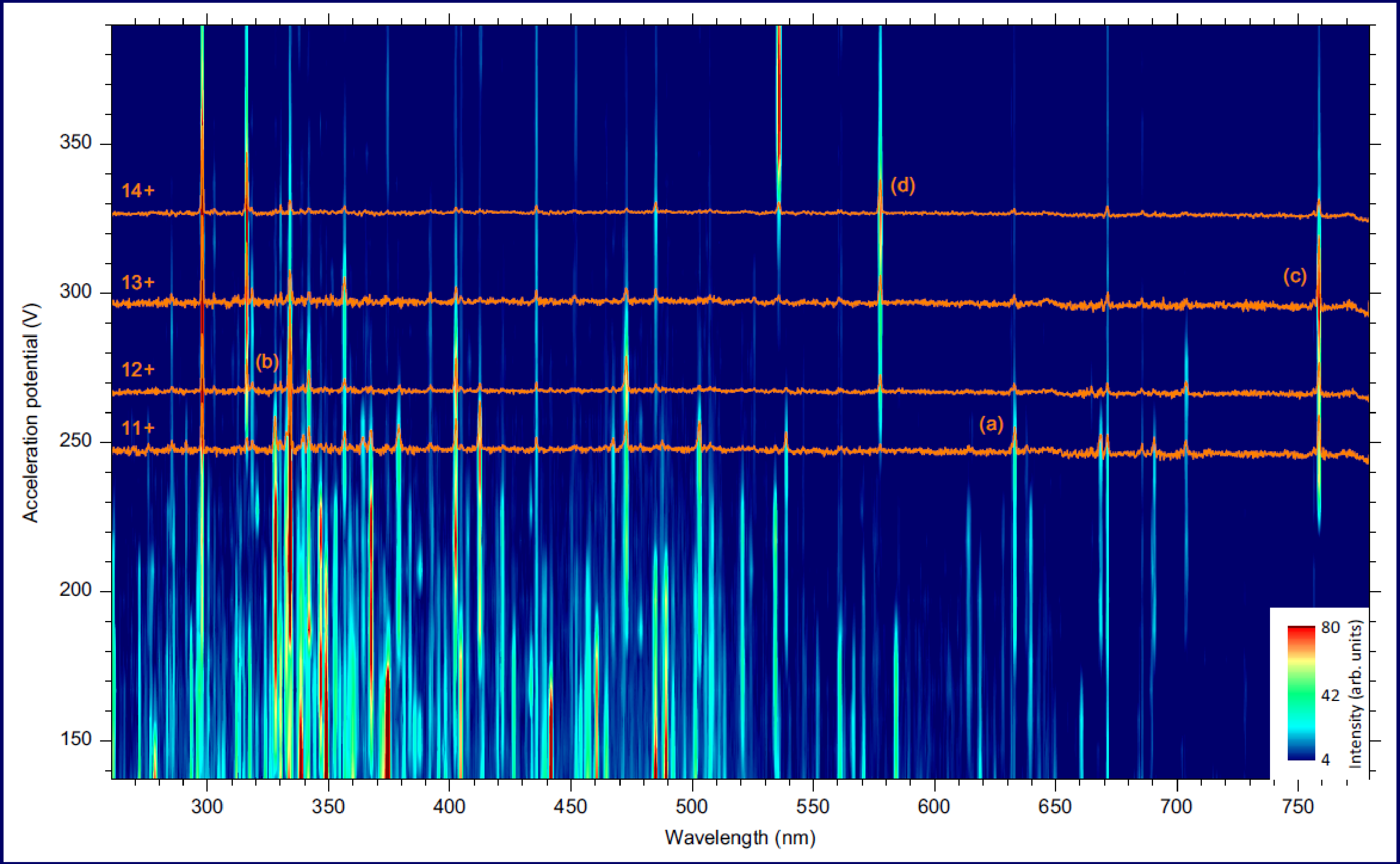
Understanding Sn spectra





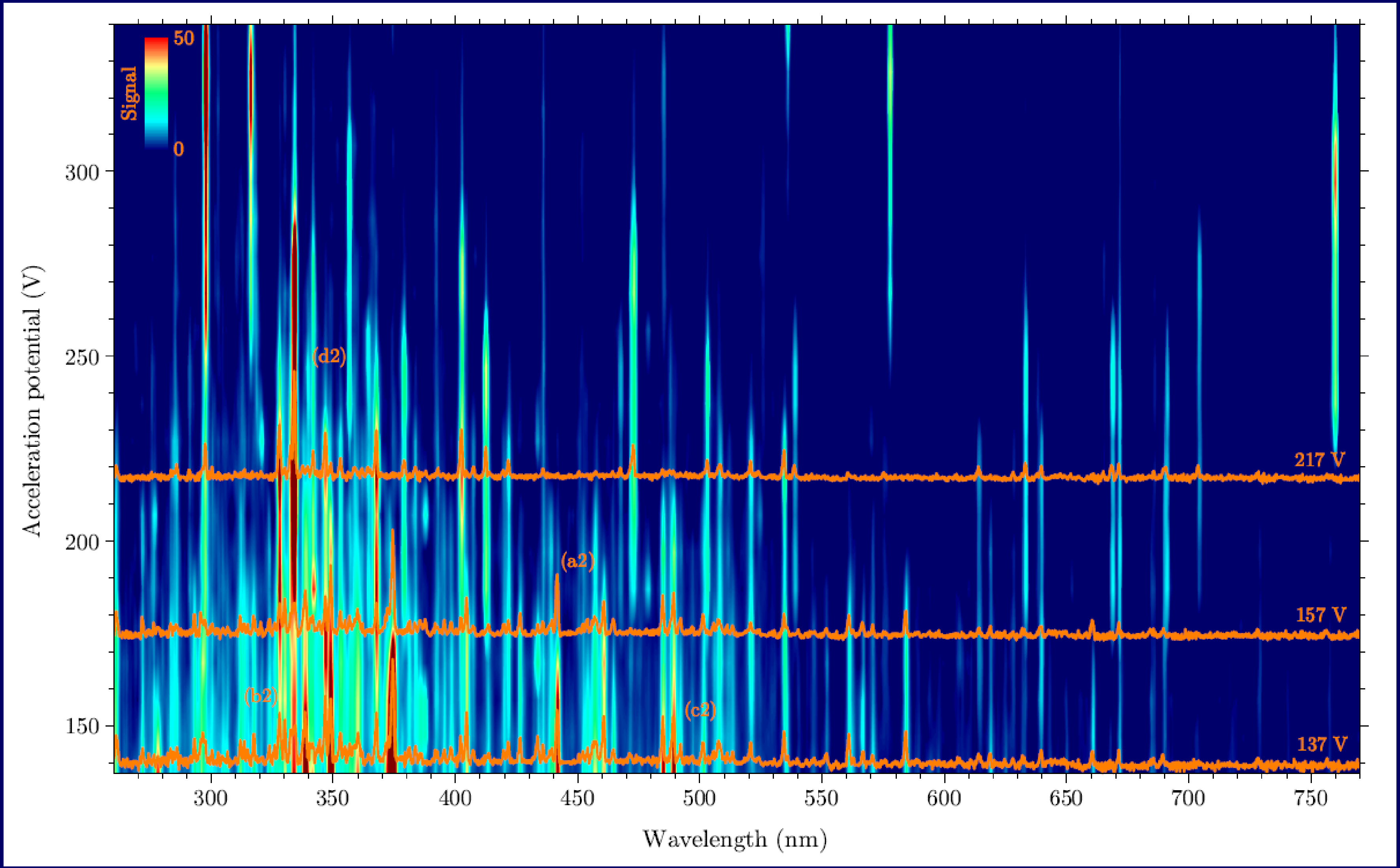
F. Torretti, ARCNL, in preparation (2016)

Understanding Sn spectra



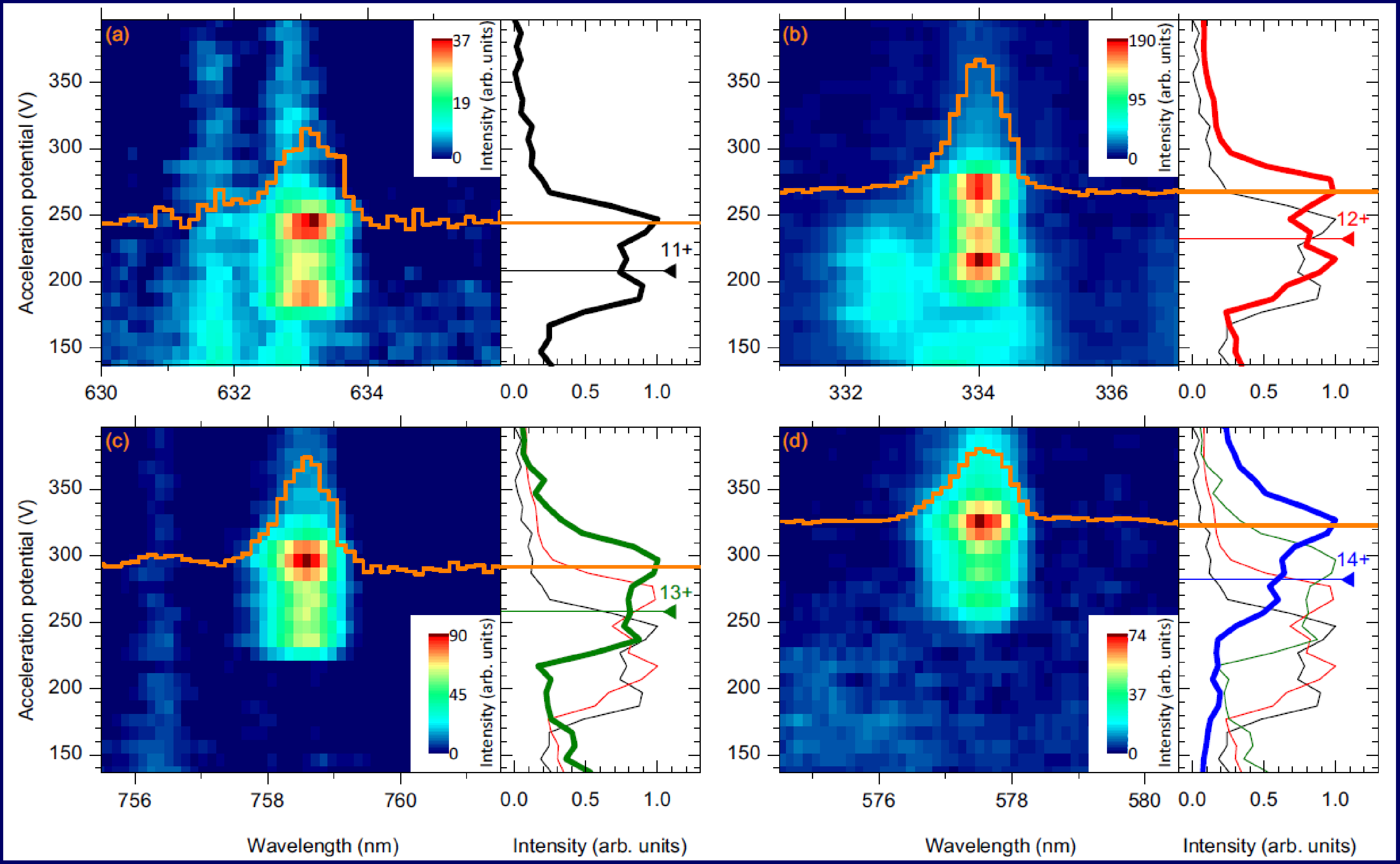
A. Windberger et al., Phys. Rev A **94**, 012506 (2016)

Understanding Sn spectra



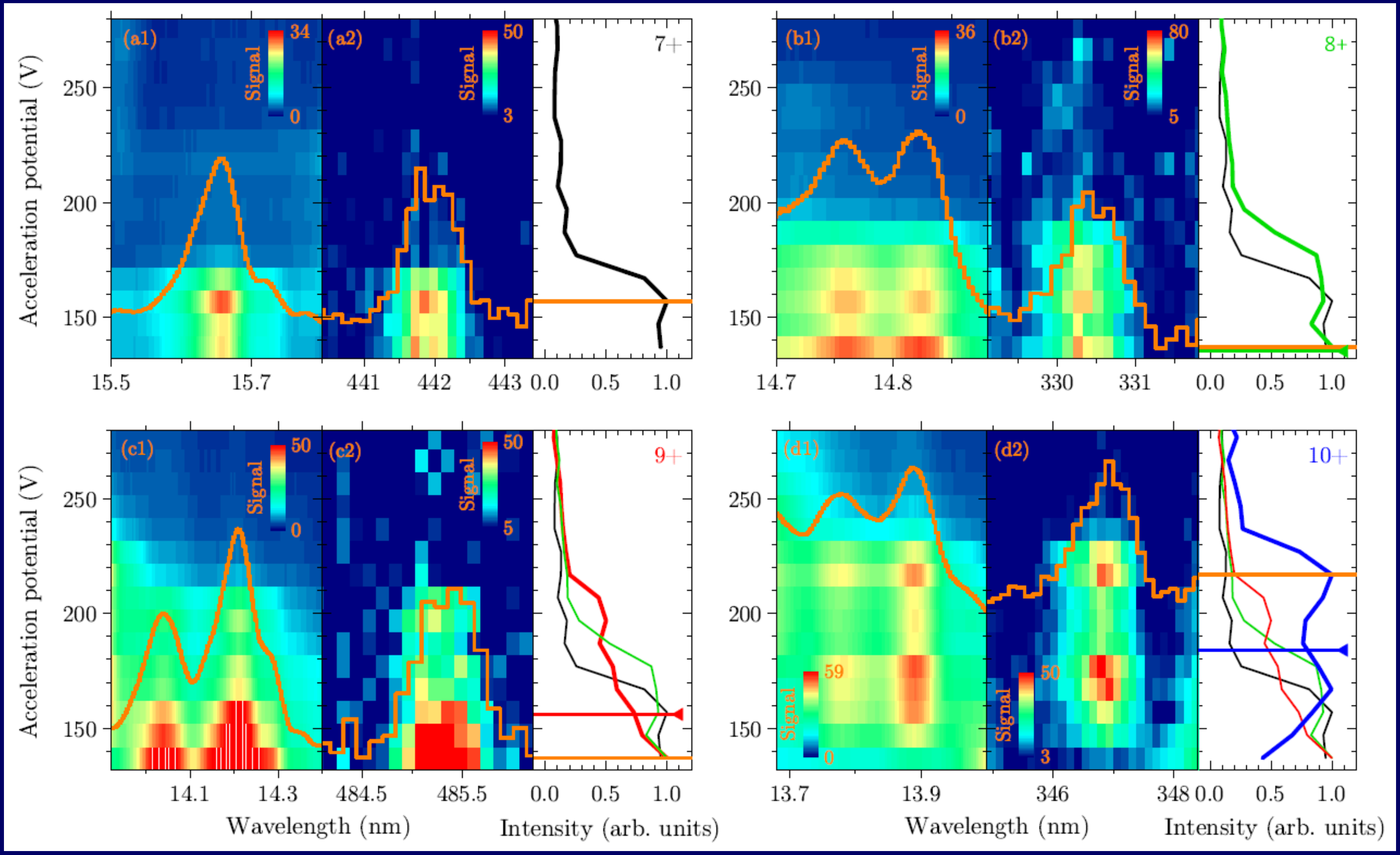
F. Torretti, ARCNL, in preparation (2016)

Understanding Sn spectra



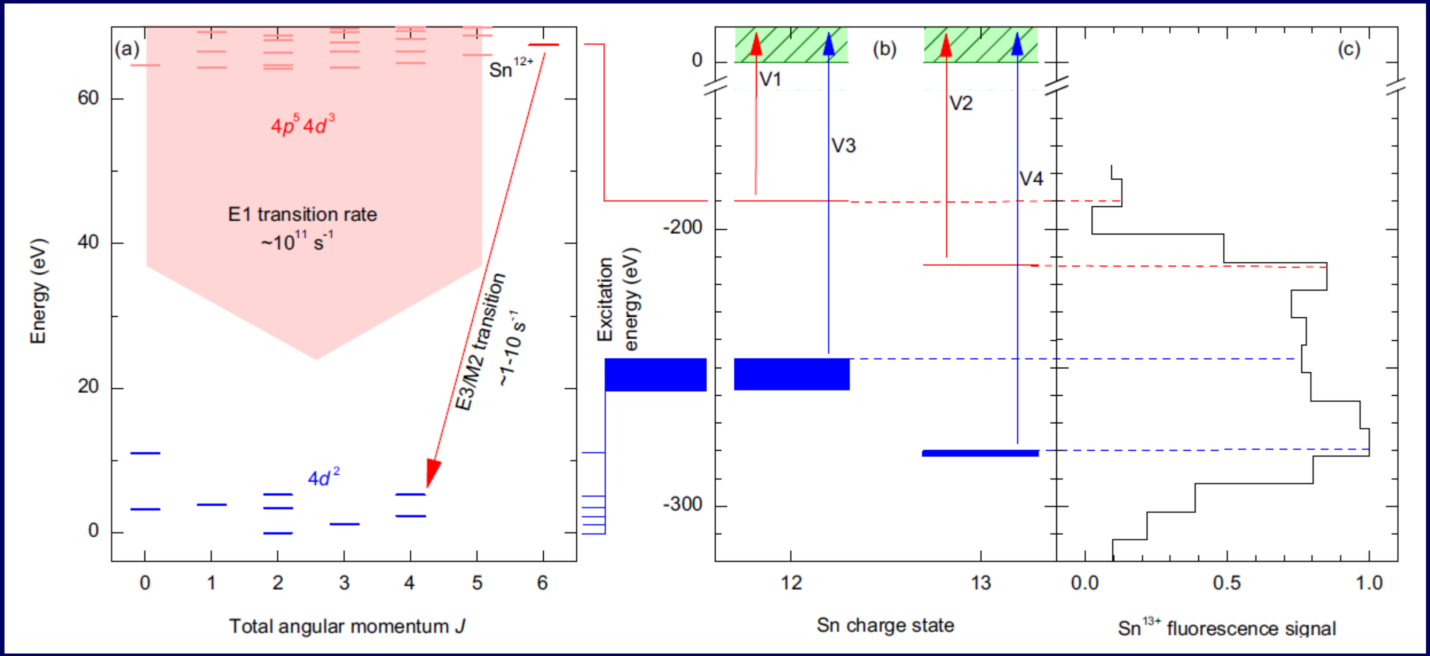
A. Windberger et al., Phys. Rev A **94**, 012506 (2016)

Understanding Sn spectra



F. Torretti, ARCNL, in preparation (2016)

Sn spectra: role of metastables



- Metastable states modify ionization dynamics and have a strong leverage in level populations and charge state
- Branching ratios and level couplings strongly depend on detailed level spacing
- Collisional-radiative modeling requires accurate atomic physics data

A. Windberger et al., Phys. Rev A **94**, 012506 (2016)

Conclusions from VIS-EUV spectroscopy

- Careful analysis of charge-state resolved optical and EUV spectra challenges some earlier identifications based on transient plasmas
- Fock-space coupled cluster (FSCC) and improved configuration interaction calculations (CI) show acceptable ab-initio accuracy, easing identification
- By calibrating Cowan-code parameters on the basis of experimental optical and EUV spectra semi-empirical line identifications can be completed

Summary

- Role of many-electron correlations is only qualitatively understood , but quantitative ab-initio calculations are challenging and require novel approaches (FSCC, improved CI and RMBPT)
- Open p, d ,f subshells challenge theory and experiment due to multi-electron resonant free-bound interactions
- Photorecombination, photoionization, electron-impact excitation as well as ionization, and charge exchange are needed to model the data
- Charge-state and electronic state-resolving studies are needed to guide theory

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